Outward and Upward Construction: A 3D Analysis of the Global Building Stock

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Abstract

The developing world has built structures on an unprecedented scale to accommodate population growth and urbanization. The horizontal and vertical structuring of the building stock resulting from this "megatrend construction" strongly influences urban and rural poverty, sustainability, resilience, and quality of life. However, due to data constraints, little is known about how and why 3D building patterns vary globally and in the developing world in particular. This study uncovers novel facts on global 3D building patterns as a result of outward and upward preferences in construction and investigates their relationship to the development process. To this end, new high-resolution data on the area, height, and volume of the global building stock are combined with various analyses undertaken at different spatial domains. The results show that building stock per capita increases convexly with income, but income only explains two-thirds of the differences in international volume. Additionally, while building upward systematically drives international volume differences, low-rise buildings still dominate construction patterns. Urbanization tends to reduce space consumption per capita as urban residents consume less volume than rural residents. Finally, the analyses of construction preferences may help to assess construction needs by forecasting volume requirements in developing Africa, Asia and Latin America.

Keywords: World Built Environment in 3D; Construction; Vertical and Horizontal Expansion; Global Socio-Economic Development; Urbanization; Housing; Poverty; Sustainability

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1. Introduction

Capturing the 3D characteristics of the building stock plays a key role in the development of sustainable and inclusive growth policies. On the one hand, a complete and accurate quantification of the building volume and density is essential to assess the efficiency, sustainability, and resilience of settlement development and urban growth (Mahendra and Seto, 2019; Bibri et al., 2020; The World Bank, 2023b). Making "cities and human settlements inclusive, safe, resilient and sustainable" is U.N. Sustainable Development Goal (SDG) 11. In addition, building volume and building density have a high influence on the local climate (Guo et al., 2022), carbon footprint (Sun et al., 2022), traffic, and mobility (Rode et al., 2017), or adaptability to natural hazards and climate change (UN Habitat, 2020). As such, these measures are also important for SDGs 12 (Responsible Consumption & Production) and 13 (Climate Action).

On the other hand, as population continues to grow rapidly in many developing regions of the world (UN, 2017), detailed information on the building volume available to residents is crucial for the provision of housing (Adetooto et al., 2022), preservation of livable cities (Lall et al., 2021), and promotion of economic development (Adabre et al., 2020). Furthermore, evidence on future construction needs is just as important as real estate (i.e., buildings) accounts for two-thirds of global wealth (McKinsey, 2021) and two-fifths of carbon emissions (UN Habitat, 2020). Also, housing represents the largest consumption item (The World Bank, 2023a) and the lack of housing is one of the main factors, if not the main factor, of urban poverty (UN Habitat, 2020).

Today, satellite imagery and computer technology allow us to map and analyze the physical form, compactness, and built-up density of settlements in 3D based on a measurement of their horizontal extent and/or vertical extent (Angel et al., 2012; Mahtta et al., 2019; Angel et al., 2021; Blei and Angel, 2021; Jedwab et al., 2021b; Frolking et al., 2022). This is especially important for developing country municipalities that do not have the administrative capacity to generate and maintain cadasters, despite how essential these are for urban planning and development (Erba and Piumetto, 2016). Recently, Esch et al. (2022), Li et al. (2022), Pesaresi and Politis (2022) and Zhou et al. (2022) generated global 3D data of the built environment that provides insights into the worldwide patterns of built-up heights and volumes. However, despite this recent progress, there is still a lack of sufficient data and knowledge at the global scale related to three issues.

Firstly, existing 3D studies still only reflect the morphological characteristics of the built-up area in general (buildings but also roads and other paved areas). For many applications, the key information needed is precise and consistent knowledge about the building stock in 3D (e.g., for estimating economic production, population distribution, or energy consumption).

Secondly, to our knowledge, most of the globally available key figures on 3D settlement morphology are currently derived from input data or analysis kernels with coarse geometric resolutions of 500m-1000m (Frolking et al., 2022; Li et al., 2022; Zhou et al., 2022).

Thirdly, systematic 3D analyses of horizontal and vertical settlement extent are often derived from between a few hundred to a thousand selected city regions (Jedwab et al., 2021b; Lall et al., 2021; Li et al., 2022; Zhou et al., 2022). The resulting empirical evidence therefore tends to favor the characteristics of urban areas, and large cities among them, focusing on developed economies rather than developing economies where most of the data needs are.

To address these limitations, this research focuses on several major improvements. Based on a unique combination of area-wide information provided by the World Settlement Footprint 3D (WSF3D) raster layer (Esch et al., 2022), with the exceptional precision of the Emporis point database of high-rise buildings (Emporis, 2022), a new dataset (WSF3Dv2) is generated with detailed information on the area, height, and volume of the building stock worldwide today. Since the data does not rely on local administrative data, the low data capacity of less developed economies does not constrain our analysis. At the same time, our data is most useful where alternative sources of data are limited, which is the case of poorer economies.

This research derives information on building area and height with a geometric resolution of 12m*12m with global coverage. Biases in terms of income status (e.g., from over-relying on data from developed economies), geographic region (e.g., driven by selection of sample regions) or settlement type (e.g., megacities) are avoided and completeness, representativeness, and general validity of the analyses and findings are assured. To meet requirements of German data security regulations (Palacios-Lopez et al., 2021) and for an open dissemination of the novel WSF3Dv2 data and derived results, all outcomes are finally provided in the form of zonal statistics (building area, building height, and building volume) aggregated to a grid of 90m*90m.

We then use the data to investigate the role of economic development in construction. National building stocks per capita increase convexly with income. Small differences are observed between low-income and lower-middle-income economies and it is only when countries become upper-middle-income economies (i.e., reach a per capita GDP of ∼$4,000) that space consumption per capita significantly increases with income. Next, we rely on the globally estimated volume-income relation to quantify global construction needs.

Developing nations in Asia and Latin America & the Caribbean (LAC) respectively account for ∼60% and ∼20% of *current* global construction needs (South Asia explains two-thirds of developing Asia's gap). African nations do not have large construction gaps because they have low incomes, and little variation in space consumption per capita is observed at such incomes.

Developing Asia then accounts for about 75% of *future*, growth-driven global construction needs when considering a horizon of five years. In developing Asia, the effects of population growth and income growth compound each other. African nations, having low incomes and low economic growth rates, do not appear prominently in the rankings despite their fast population growth (developing LAC's contribution is also small). Lastly, focusing on future construction needs by 2050, and only taking into account population growth, developing Africa, Asia and LAC now respectively account for ∼50%, ∼25% and ∼5% of *current* global construction needs.

We then use the data to unpack how outward construction (building area) and upward construction (building height) account for the volume-income relation observed globally. We find that vertical expansion is the main driver of international volume differences, as it accounts for ∼60% of the global volume-income relation, including in the developing world. Low-rises below 50 m, not high-rises, then account for ∼90% of the contribution of upward construction.

Given that urban residents consume less space per capita than rural residents, urbanization should tend to reduce per capita consumption, and thus cannot account for the higher levels of space consumption in more developed economies. We find that rural areas & small towns differ more across countries in terms of volumes than urban areas do, as a result of which rural areas & small towns explain ∼60% of international volume differences. Lastly, upward construction and low-rises drive international volume differences in both types of areas.

Finally, we employ residualization procedures to classify large countries and cities with similar levels of economic development into pro-heights vs. pro-area and pro-high-rises vs. pro-low-rises for their heights. Asian nations and megacities are more pro-heights than African or LAC nations and megacities. LAC is more pro-high-rises for its heights whereas Africa is more pro-low-rises. Asia has a more balanced height distribution. Eastern Europe is more pro-heights than Western Europe or North America (they are all pro-high-rises for their heights).

Policy-wise, the results suggest that: (i) economic development does not fully explain international volume differences, as one-third of volume differences can be attributed to other factors, which likely include land use regulations such as height restrictions and urban containment policies (e.g., greenbelts and urban growth boundaries); (ii) land-use regulations are likely not as consequential in lower income countries where little variation in space consumption levels are observed; (iii) existing land-use regulations may become more binding in the future as some regions of the world keep experiencing fast population growth, including Africa and South Asia; (iv) countries and cities with similar income levels vary in their upward vs. outward specializations, suggesting again an important role for height restrictions and urban containment policies; and (v) meeting construction needs could have important environmental implications because the construction sector accounts for ∼40% of carbon emissions (UNEP, 2022). Likewise, a nation's or city's outward or upward specialization could have environmental implications if sprawl or skyscrapers disproportionately produce carbon emissions (e.g., either because of gasoline cars or the construction materials used) (The World Bank, 2023b).

In addition to literature on how construction patterns vary across world regions, countries, and cities, we contribute to literature on the characteristics of the urbanization process globally, and in the developing world in particular. Urban areas only account for ∼40% of global volumes and international volume differences. Given that urban residents typically consume less space per capita than rural residents, urbanization should reduce space consumption per capita. At the same time, many nations and cities have low levels of space consumption per capita, implying that they may need to build more vertically and/or horizontally. Studies have shown how historically crowded the cities of many developing countries are (Castells-Quintana, 2017; Jedwab et al., 2017; Jedwab and Vollrath, 2019). Many developing countries are also "urbanizing without growth" (Fay and Opal, 2000; Fox, 2012; Jedwab and Vollrath, 2015; Gollin et al., 2016; Fox and Goodfellow, 2016; Castells-Quintana and Wenban-Smith, 2020). At the same time, meeting global construction needs could have dramatic environmental consequences. There are thus trade-offs between promoting housing affordability and ensuring livability/sustainability.

There is then the question of whether it is more optimal to meet construction needs by building upward or outward. Verticality is associated with compact and economically dense cities (Lall et al., 2021; Ahlfeldt et al., 2023; The World Bank, 2023b), which favors economic efficiency and innovation as shown by a large literature on agglomeration economies (Duranton and Puga, 2004; Castells-Quintana and Royuela, 2014; Combes and Gobillon, 2015; Chauvin et al., 2017; Duranton and Puga, 2020). Horizontality produces sprawl and congestion (Duranton and Turner, 2011; Jedwab et al., 2022; Akbar et al., 2023). However, the skyscrapers of many developing countries constitute white elephant projects that are economically and environmentally inefficient (Gjerlow and Knutsen, 2019; Ianchovichina et al., 2022; Jedwab and Roberts, 2023). Finally, nations and cities of similar income levels can differ in their specialization in heights or areas. These specializations likely reflect differences in land-use regulations and institutions more broadly, as shown by studies on individual regions, countries, cities (Brueckner and Sridhar, 2012; Fox, 2014; Brueckner et al., 2017; Brueckner and Singh, 2020) or skyscrapers globally (Jedwab et al., 2022; Jedwab and Barr, 2023b,a). We instead consider the whole building distribution.

2. World Settlement Footprint 3D: From Version 1 to Version 2

The first version of the World Settlement Footprint 3D (WSF3Dv1) dataset, released in 2017, provides information on the building fraction (BF), height (BH), and volume (BV) at 90 m spatial resolution (Esch et al., 2022). WSF3Dv1 was created based on a global coverage of 12 m digital elevation (TDX-DEM) and Synthetic Aperture Radar (SAR) data (TDX-AMP) collected by the TanDEM-X satellite mission in 2012-2013 (Zink et al., 2014), in combination with 10 m resolution multispectral Sentinel-2 (S2) satellite imagery. Although the analyses are performed at a gridding of 12 m, the final WSF3D products can only be made publicly available with a reduced resolution of 90 m due to German data security regulations (SatDSiG) related to the TanDEM-X mission.

The WSF3Dv1 analysis framework introduced by Esch et al. (2022) consists of three automated processing modules: a first workflow defines the building fraction (BF) within each 90 m grid cell based on TDX-DEM, TDX-AMP, and S2. The second module analyzes height differences occurring along building edges in the TDX-DEM elevation data to derive the average building height (BH) at 90 m gridding. A last processing workflow combines the previously derived BF and BH information to calculate the building volume (BV).[1]

To determine the building fraction BF, the temporal maximum of the Normalized Difference Vegetation Index (NDVI_max) is calculated for all WSF2019 pixels from a time series of $\sim$2.27 million S2 granules with $<$ 60% cloud cover (level 2A, bottom of the atmosphere reflectance) acquired in 2018-2019 (Marconcini et al., 2020). Using NDVI_max and building footprint data from OpenStreetMap (OSM, 2017), an ensemble of support vector regression models is trained separately for all Köppen-Geiger climate zones to estimate the BF for each WSF2019 settlement pixel.[2] The resulting information on BF (%) can be employed to define the total building area BA (m^2) of each cell by applying BF as a multiplication factor to the cell's 12*12 m ground area.

The generation of the building height (BH) product is based on analyzing local height differences at vertical edges (VE) in the 12 m resolution TDX-DEM within the settlement area of WSF2019. In the TDX-DEM, VEs appear as distinct punctual or linear height variations along the outlines of quasi vertical structures such as buildings, walls, trees, or hedgerows. A given pixel in TDX-DEM is considered as a VE candidate if the ratio between the height of the target pixel (above sea level) and the median height (ditto) in its immediate neighborhood (within a 5 x 5 moving window) is $>$ 1.0 (Esch et al., 2022). Since the natural slope of the local terrain also leads to height differences, the slope-induced height differences are factored out by normalizing the measured local edge height VE with the local slope of the terrain. The terrain slope is measured by first removing all local maxima and vertical edges (TDX-DEM pixels where VE $>$ 0.0) before filling the resulting local gaps in the TDX-DEM elevation data with a four-direction conic search distance weighting (Esch et al., 2022). This generates an edge-smoothed version of the TDX-DEM that only shows height differences due to the local terrain, whereas previously included height structures in the original TDX-DEM that arose from local vertical objects are now leveled in. By subtracting the edge-smoothed version of TDX-DEM from the original TDX-DEM, the effect of slope-induced height differences is minimized so that the resulting VE layer only shows

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[1] Note that all analyses are exclusively carried out for areas assigned as settlement by the World Settlement Footprint 2019 (WSF2019) human settlements mask (Marconcini et al., 2021).

[2] Empirical tests with a WSF settlement mask and WSF-IMP layer generated on the basis of 30 m Landsat data collected in 2012 (meaning the exact time of the TDXDEM data acquisition) clearly indicated the superiority of the WSF mask and WSF-IMP information derived from the 10 m S2 data (not yet available in 2012), although the imagery was collected in 2019. Indeed, the WSF2019 settlement mask, although including additional settlement areas that arose between 2012 and 2019, still shows a higher accuracy compared to the settlement mask derived from the coarse 30 m Landsat imagery. Moreover, the imperviousness estimation at 10 m based on NDVI_max from 2019 S2 data led to a more precise masking of urban green spaces compared to the results obtained from Landsat.

the actual height variations along local vertical structures. Since VE can still include vertical vegetation structures such as trees or hedges, all VE-candidate pixels dominated by vegetation are masked out. For this purpose, an ensemble of support vector regression models is trained separately on the NDVI_max layer for all Köppen-Geiger climate zones to estimate the percent impervious surface (IMP) within each WSF2019 pixel. Based on the resulting WSF-IMP, all VE candidate pixels showing a value < 10 (meaning that more than 90 % of the pixel area is covered by vegetation) are masked out. To produce the final BH product, all local height differences observed for the remaining VE pixels are then spatially aggregated from their 12 m resolution to a 90 m cell by calculating the mean of all VE heights observed within this cell.

As reported in Esch et al. (2022), the BH layer of the WSF3Dv1 shows certain inaccuracies due to the systematic underestimation for the heights of high-rise ($>$ 50 m) buildings. In dense, high-rise areas, complex and compact morphological structuring leads to multiple scattering, layover, and shadow effects causing ambiguities in the SAR signal, which ultimately results in errors in the absolute heights provided by TDX-DEM.

Thus, information from Emporis (EM) for the year 2019 is now integrated to create an enhanced version of World Settlement Footprint 3D (WSF3Dv2). EM is the most complete collection of global skyscraper and high-rise building data (see Appendix Section B for details). They rely on information provided by the industry for "thousands of cities worldwide. Emporis (2022) collects information about the full life-cycle of each building. The database (last accessed 09-07-2022) contains information for 781,136 completed tall buildings.

Technically, the improvement of the BH layer is based on a correction factor (fxy) calculated using the relative differences between spatially overlapping BH values derived from WSF3Dv1 (BHv1), and EM building height values (BHEM) provided for the exact geographical coordinates of all buildings as defined in eq. (1) and (2):

$$f_{xy} = 0.90(BH_{EM} - BH_{v1})_{xy} \tag{1}$$

$$(BH_{v2})_{xy} = (BH_{v1} + f_{xy}) \tag{2}$$

The application of a 90% adjustment factor f$_{xy}$ (instead of directly using the EM-provided height at the xy location) is dictated by the need to prevent the original, license-protected EM information from being reconstructed from the resulting BHv2 layer.

In a second processing step, EM is also used for BH outlier detection and removal. As EM is supposed to be globally complete for all buildings $>$100 m (see Appx. Section B), BHv1 pixels showing a BH $>$100 m and not having any EM point in a 3x3 neighborhood (BHv1xy $\notin$ EM), are considered as outliers. However, as the WSF2019 settlement mask indicates the presence of buildings at this location, the actual BH value is not completely removed, but drastically reduced by applying an adaptation factor of 0.01 to the current BH value as shown in eq. (3):

$$(BH_{v2})_{xy} \notin EM = 0.01 * (BH_{v1})_{xy} \notin EM \Rightarrow (BH_{v2})_{xy} \notin EM > 100m \tag{3}$$

Next, for BH pixels showing a height between 50-100 m without an EM point in their vicinity (meaning here, EM is still supposed to be reasonably complete), we assume that BH is overestimated because otherwise EM should indicate the presence of a high-rise. In this case, the BHv1 value is reduced by 90% of the difference between the current BHv2 value and a fixed virtual height of 50 m (see eq. (4)). The 50 m height is used because it represents the empirically determined completeness threshold for tall buildings in EM (see Appx. Section B):

$$(BH_{v2})_{xy} \notin EM = (BH_{v1})_{xy} \notin EM + 0.01(50 - BH_{v1})_{xy} \notin EM \Rightarrow 50m < (BH_{v2})_{xy} \notin EM > 100m \tag{4}$$

In order to generate the new building volume product BVv2 (m^3), the BHv2 building heights are merged with the building areas given by BAv1. See eq. (5).

$$BV_{v2}, 90m[x,y] = BH_{v2}, 90m[x,y] * BA_{v1}, 90m[x,y] \tag{5}$$

The improvements in BH achieved by integrating EM are documented by a comprehensive global validation campaign (see Appx. Section A for details). The WSF3Dv2 data can be accessed free and open at: https://geoservice.dlr.de/web/maps/eoc:wsf3d. Likewise, the replication files for the analysis and the country- and city-level data sets can be found here: https://doi.org/10.7910/DVN/TQ1AS5.

In Figure 1 below, this improvement can be observed in Manhattan by comparing the BH (building height in m) layer of the original WSF3Dv1 (top-right panel B) and the EM-improved WSF3Dv2 (bottom-left panel C). The top-left panel A shows the BA (building area in m^2) layer, whereas the bottom-right panel D shows the BV (building volume in m^3) layer. Redder pixels have more buildings (A), taller buildings (B-C), or more voluminous buildings (D).[3]

Figure 2 illustrates the distribution of WSF3Dv2 heights for selected areas. Redder bars indicate a higher frequency of taller buildings. Asia has more tall buildings than Africa and Latin America, and Europe has more tall buildings than North America. China has taller buildings than the U.S. India has almost as many tall buildings as the United Kingdom. Seoul appears as tall as New York. Bogota, Cairo, Karachi, Paris, and Lagos are relatively flat.

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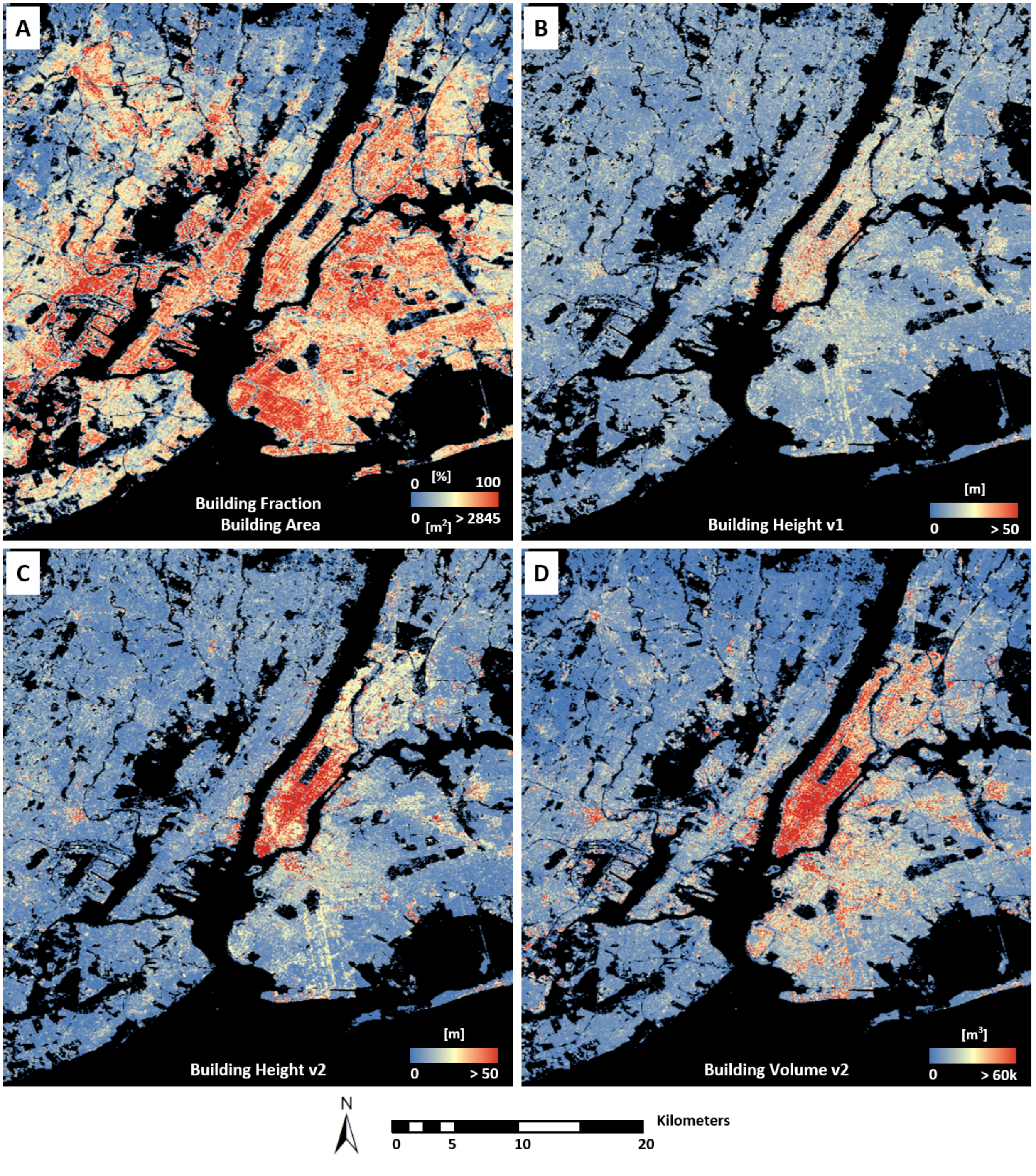
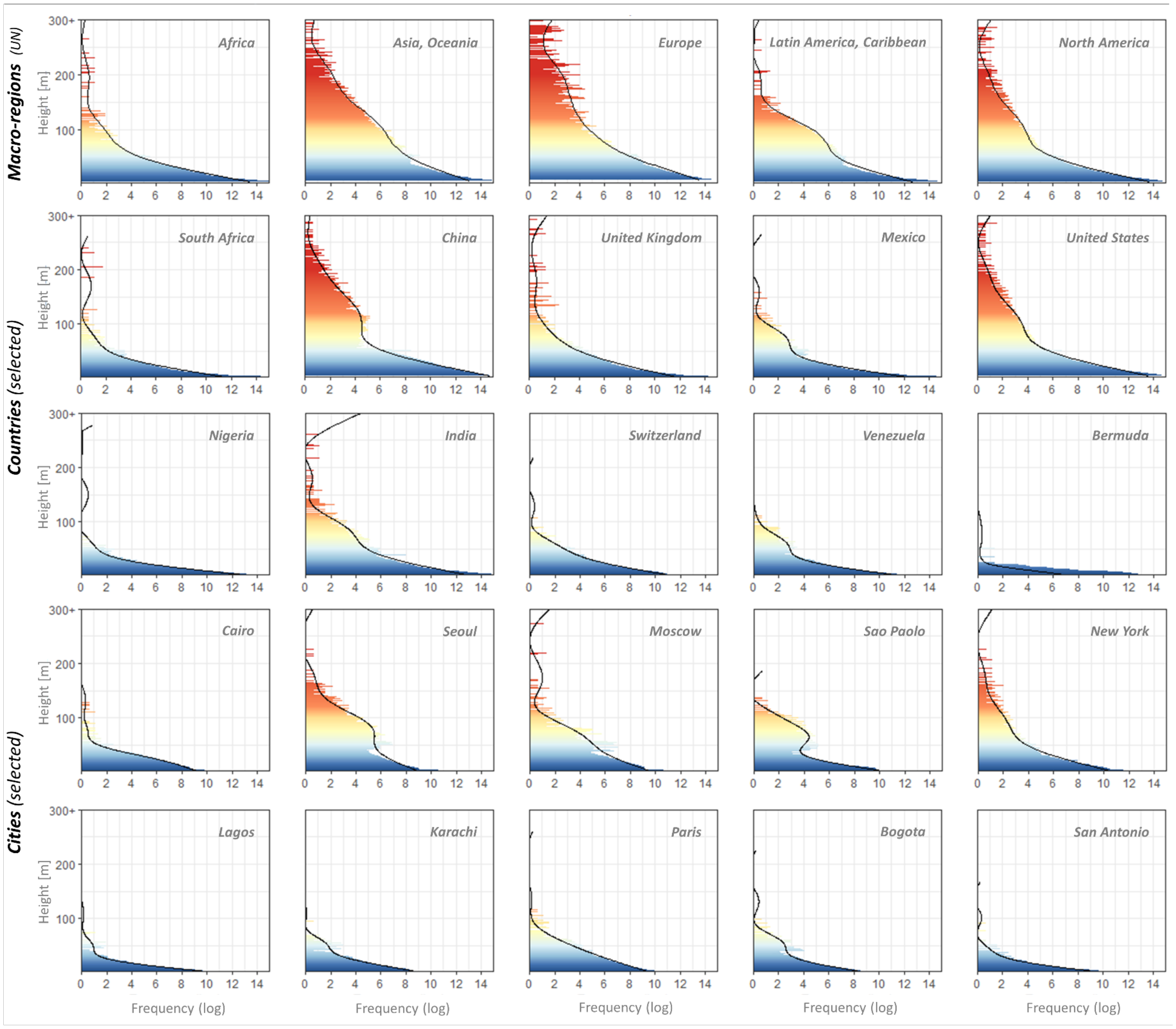
[3] Appendix Figures C.1 and C.2 show the maps for some of the world's largest cities and at global scale, respectively.

Figure 1: Building Area, Height and Volume for New York City’s Region, 2012/2019



Notes: The figure shows New York City’s region in WSF3D (90m*90m resolution). Building area is in m^2 (A). Height is in m in WSF3Dv1 (B) and WSF3Dv2 (C). WSF3Dv2 volume is in m^3 (D). Data is for the year 2012/2019.

Figure 2: Global Distribution of Building Heights Derived from the WSF3Dv2 Data.



Notes: Exemplary height plots for selected macro-regions, countries and cities illustrating the wide variety of patterns in upward and outward settlement extent. Redder bars indicate a higher frequency of taller buildings. “Frequency (log)” on the x-axis indicates that we report the log of the number of pixels for each height bin (meters).

3. Background

The total global building volume equals 1,593 billion m^3 ($\sim$1.52 million Empire State Buildings), resulting from a total building area of $\sim$300,000 km^2 and a mean height of $\sim$5 m. We obtain 1,558 billion m^3 in WSF3Dv1, implying that it missed 2% of global volumes. WSF3Dv2 mostly improves upon WSF3Dv1 for cities, where WSF3Dv1 missed 5% of global volumes (we get 9% for cities above 5 million today). Indeed, WSF3Dv1 disproportionately missed high-rise buildings and skyscrapers typically found in cities. This holds as well in the developing world where the same missing shares are 2%, 4%, and 8%, respectively. Focusing on cities, the volume discrepancy between WSF3Dv2 and WSF3Dv1 is then larger for the developing economies of Latin America & the Caribbean (LAC) (7%) than in developing Asia (3%) or Africa (1%).

Regional statistics from WSF3Dv2 are provided in Table 1. Developing economies account for two-thirds of global volumes. Upper-middle, lower-middle, and low income economies account for 70%, 25%, and 5% of total volumes in the developing world, respectively. Africa accounts for 9% of global volumes despite comprising almost 18% of the world's population.

Table 1: Selected summary statistics for several groupings of countries, 2012/2019

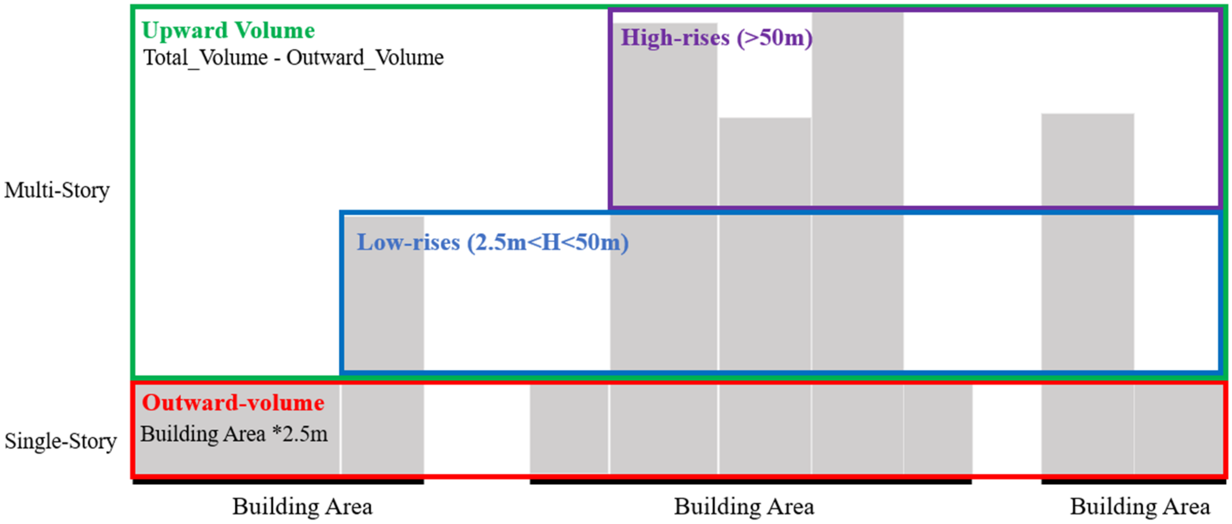
Economies	Volume km^3	Per Cap. m^3	% Outward	% Upward	% Low-Rise	% High-Rise
World	1593	207	52	48	46	2
Developed	577	467	43	57	53	4
Developing	1016	157	54	46	45	1
High-Income	577	467	43	57	53	4
Upper-Middle-Inc.	705	246	46	54	52	2
Lower-Middle-Inc.	254	87	59	41	40	1
Low-Income	55	83	68	32	32	0
Africa	148	113	65	35	35	0
Asia	749	164	50	50	48	2
Europe	372	498	43	57	55	2
Latin America & Carib.	115	177	54	46	43	3
North America	193	526	47	53	51	2
Pacific	16	375	54	47	45	2

Notes: This table shows summary statistics for four groupings of countries. Developed Status is based on the World Bank (WB)'s classification of countries in 2019 (= high-income economies). Outward volume = built area x 2.5m. Upward volume = volume - outward volume. High-rise volume = from high-rises ($\geq$ 50 m). Low-rise volume = from low-rises (between 2.5m and 50m).

In general, the mean volume per capita in the world is $207m^3$. Assuming housing accounts for half the building stock and a ceiling height of 2.5m, the average resident occupies $40m^2$. But volume per capita in low- (LIC), lower-middle (LMIC), upper-middle (UMIC), and high-(HIC) income countries is 83, 87, 246, and $467m^3$, respectively. Thus, the average resident in LICs, LMICs, UMICs, and HICs possibly occupies 17, 17, 49, and $94m^2$ of living space.

Considering the building area and assuming buildings are single storey (with an average floor height of 2.5m) results in a total contribution of outward (horizontal) volume to total volumes of 52%, with upward (vertical) volume accounting for the rest (48%). Upward volume is then decomposed into low-rises (2.5-50m) and high-rises (>50m), which respectively account for 46% and 2% of global volumes, respectively. See Figure 3 below for details on how the total volume is decomposed into outward volume and upward volume from low-rises and high-rises.

Figure 3: Volume Decomposition Used: Upward vs. Outward, High-Rises vs. Low-Rises



Notes: This figure shows a schematic of the volume decomposition used in this study for the definition of i) *Outward volumes* (building area x 2.5m, because we assume buildings are single storey) and ii) *Upward volumes* due to a) *High-rises* (buildings > 50m) or b) *Low-rises* (hence, buildings between 2.5m and 50m).

4. The Role of the Development Process

Having confidence in the new WSF3Dv2 data, we use it to unpack the role of the development process in overall construction and space consumption. Having characterized the construction-income relationship, we proceed to identify countries and world regions with possibly larger construction "gaps" as well as countries and regions that may have to build significantly more space in the future due to income and/or population growth.

4.1. The Relationship between Building Stocks and Economic Development

As shown in Figure 4, the relationship between volume per capita and income is convex as the volume per capita increases more steeply between higher income countries rather than between lower income countries (see the "overall" line).[4] Almost no differences are observed between low income and lower-middle income economies. Using a more flexible local polynomial fit (not shown), the log income level at which volume per capita starts increasing is 8.3, or ∼\$4,000, the

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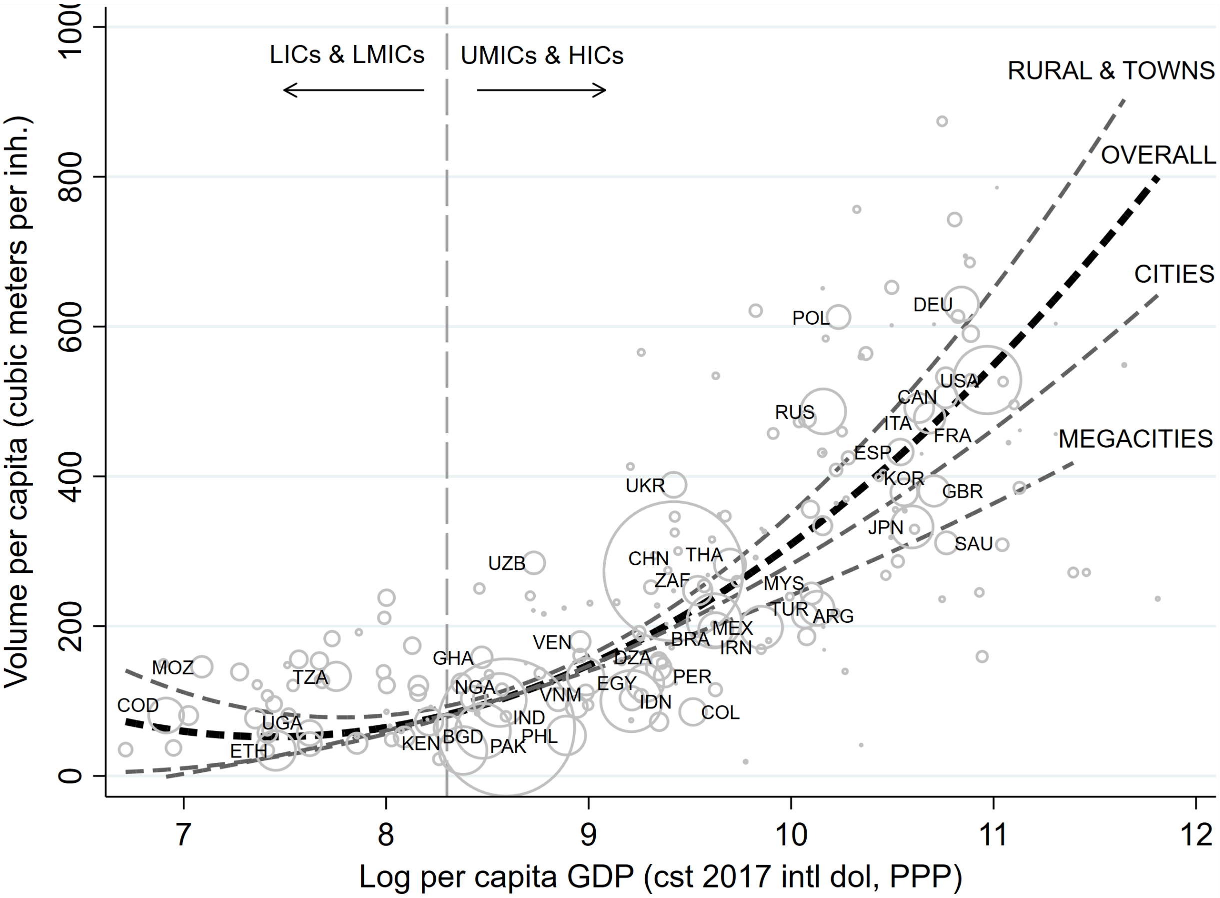
[4] Volume per capita in 2012/2019 and log mean per capita GDP in the 2010s (we rely on the *World Development Indicators* database of the World Bank to obtain annual GDP per capita in PPP terms and constant 2017 international dollars and employ a decadal average to capture permanent economic conditions).

threshold used by the World Bank to distinguish LMICs and UMICs.

Figure 4: Volume Per Capita and Economic Development, 2010s.



Notes: The figure illustrates the relation between volume per capita in 2021/2019 and log mean per capita GDP 2010-2019 for 204 countries. It also shows the relation for "rural areas & towns", "cities", and "megacities". It uses populations as weights. The size of the bubbles indicates the countries' populations in 2019.

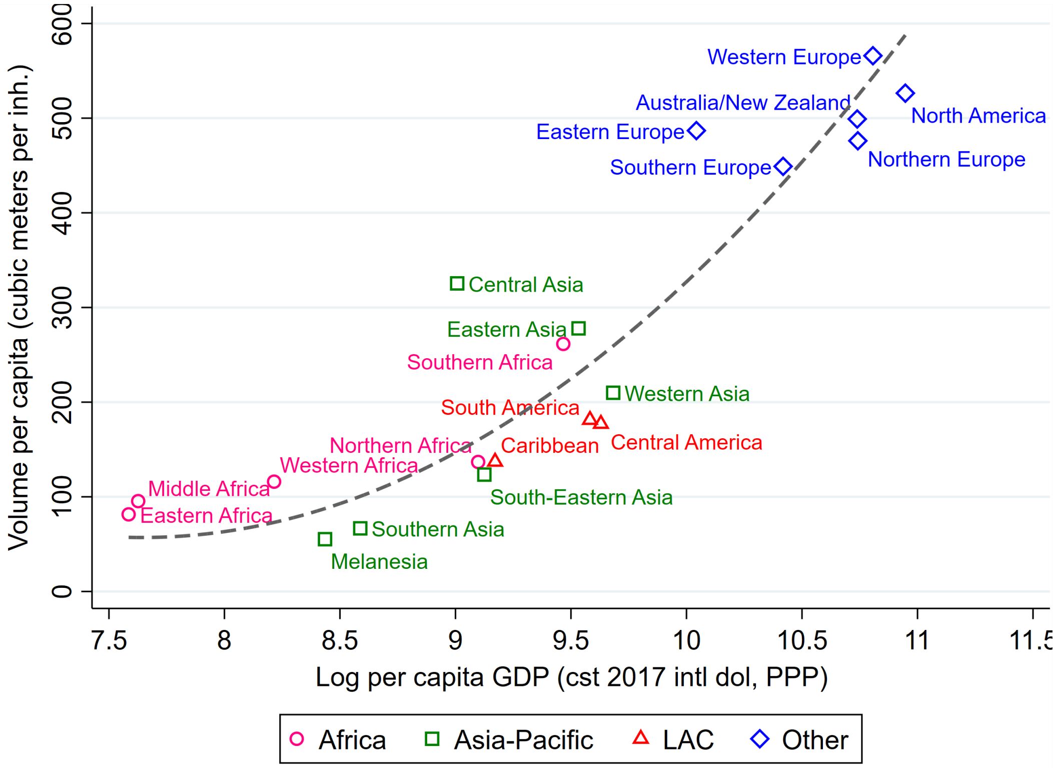
Economic development shapes construction patterns. Indeed, individuals and firms in richer regions demand and use more space that is in turn supplied thanks to more efficient construction technologies and sectors (Ahlfeldt et al., 2023). However, in LICs and in LMICs where space is needed the most due to fast-growing populations (UN Habitat, 2020; Jedwab and Vollrath, 2019; Jedwab et al., 2017), the economies and policies are simply not strong enough.

While income has a strong relationship with a nation's capacity to accommodate its population, the results also indicate that it only explains two-thirds of the volume differences across countries. The R-Squared is 0.68, implying that one-third of volume differences can be attributed to other factors. For example, the average German resident occupies 19% more volume than the average U.S. resident, who in turn occupies 39% more volume than the average British resident. Ghanaians and Tanzanians occupy 56% and 133% more space than Nigerians and Ugandans, respectively. These countries have similar levels of economic development.

However, likely due to differences in policy, they offer different space to their residents.

Figure 5 shows the relation for 20 U.N. subregions. Subregions above the line such as Eastern Europe, Central Asia, Eastern Asia and Southern Africa have more volume per capita for a given per capita income level. Conversely, subregions below the line such as North America, Northern Europe, Western Asia and Central America have less volume per capita for a given income level.

Figure 5: Volume per Capita and Economic Development, 20 UN subregions, 2010s.



Notes: This figure shows for 20 U.N. subregions the relation between volume per capita in 2019 (m^3 per inhabitant) and log mean per capita GDP in 2010-2019 (in PPP terms and constant 2017 international dollars).

Overall, countries and regions with more space per capita for a given income level may be more laissez-faire due to less stringent height restrictions or urban containment policies or efficient permitting processes (Jedwab et al., 2021a; Jedwab and Barr, 2023b). Consequently, housing is cheaper and employment more robust (Ahlfeldt et al., 2023; The World Bank, 2023b). However, if countries use more space per income, they have less compact localities, with implications for the environment and society (UN Habitat, 2020; The World Bank, 2023b).

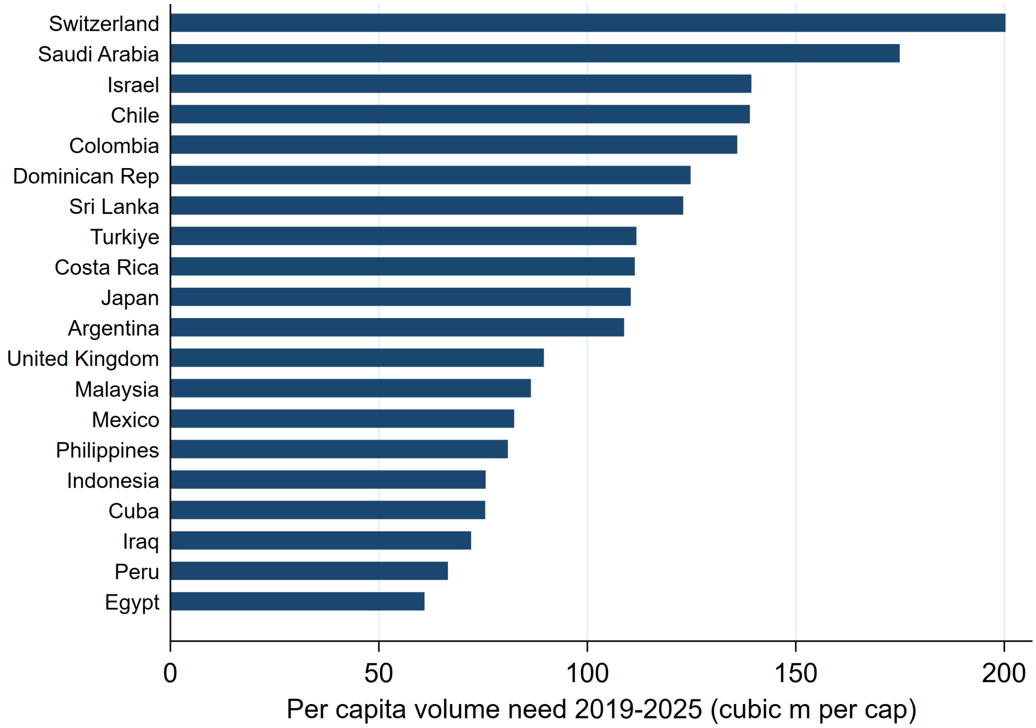
4.2. Quantifying Current Global Construction Gaps

Countries located “below” the world line in Figure 4 have less volume per capita than other countries given their level of economic development. For each country below the world line, we estimate how many cubic meters they need to get to the line, hence their construction gap.

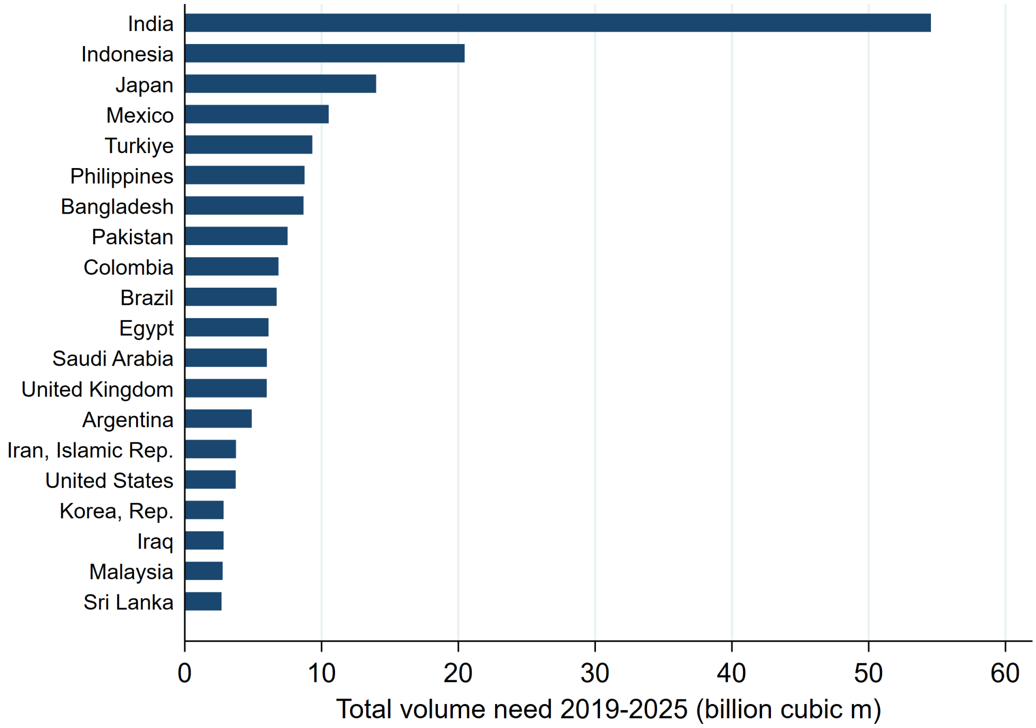
Figure 6 lists the top 20 economies in terms of potential current construction needs.

Figure 6: Potential Current Construction Needs, Top 20 Economies, 2012/2019.

(a) Current Per Capita Volume Needs (Cubic m per capita)



(b) Current Total Volume Needs (Billion cubic m)



Notes: The top panel and the bottom panel show the top 20 economies in terms of current (2012/2019) predicted per capita construction needs (m^3 per capita) and total construction needs (billion m^3), respectively. Note that we exclude countries with a population below 5 million residents as of 2019 as well as several city-states.

In per capita terms, the list includes many MICs (Argentina, Colombia, the Arab Republic of Egypt, Indonesia, Mexico, and Türkiye). Focusing on total volume, the list is dominated by populated developing economies with large per capita needs (India, Indonesia, Mexico, Türkiye, the Philippines, Bangladesh, Pakistan, Colombia, Brazil, and Egypt). LICs are absent from the lists as there is less variation in volumes per capita at low income levels than at intermediary income levels.

Only considering developing economies below the line, the mean per capita gap is 24 m^3 in Africa, 47 m^3 in Asia, and 65 m^3 in LAC (respectively 5 m^2, 9 m^2, and 13 m^2 assuming a housing share of 50% and a 2.5. m ceiling height). However, for total volume needs, we get 15 billion, 125 billion, and 36 billion m^3, respectively. More generally, developing Asian economies account for $\sim$60% of the world gap (vs. 17% for developing LAC and 7% for Africa), with South Asia explaining two-thirds of developing Asia's gap, and India contributing to $\sim$70% of South Asia's gap. India might need to build 54 billion m^3, more than half of its current stock. For Indonesia, it is 20 billion m^3, one-third of its current stock. Globally, bridging the gap would increase stocks by $\sim$14%.

However, other factors could affect the economic, social, and environmental "optimality" of construction patterns. Bridging the gap could have dramatic effects on the environment, given the building sector accounts for 39% of carbon emissions worldwide (UNEP, 2022). Meeting the estimated global needs would increase global carbon emissions by $\sim$5%, implying trade-offs between promoting housing affordability and ensuring livability/sustainability.

4.3. Quantifying Future Global Construction Needs

4.3.1. Forecast until 2025

The forecast of future, growth-driven construction needs is a crucial tool in view of a fast-urbanizing world and unaffordable cities (UN Habitat, 2020; The World Bank, 2023b). With estimates of the future population and income of a country, we can quantify by how much the country's volume must increase to match global construction trends. From the estimated quadratic fit in Figure 4, we obtain coefficients α (2,209***), β (-580***) and γ (39***) in eq. (6):

$$Volume/Population = \alpha + \beta * log(GDP/Population) + \gamma * (log(GDP/Population))^2 \qquad (6)$$

Using data from the World Bank (2019), we obtained the predicted real GDP growth rate of each country in 2019-2022. We consider countries from the viewpoint of 2019, thus ignoring the unrelated economic effects of the COVID-19 pandemic. Using the average annual growth rates in 2019-2022, we estimate each country's GDP in 2025. From the United Nations (2019), we obtained each country's predicted population in 2025 (ignoring COVID-19 mortality).[5]

Equation (6) is used to estimate how Volume/Population may need to change as

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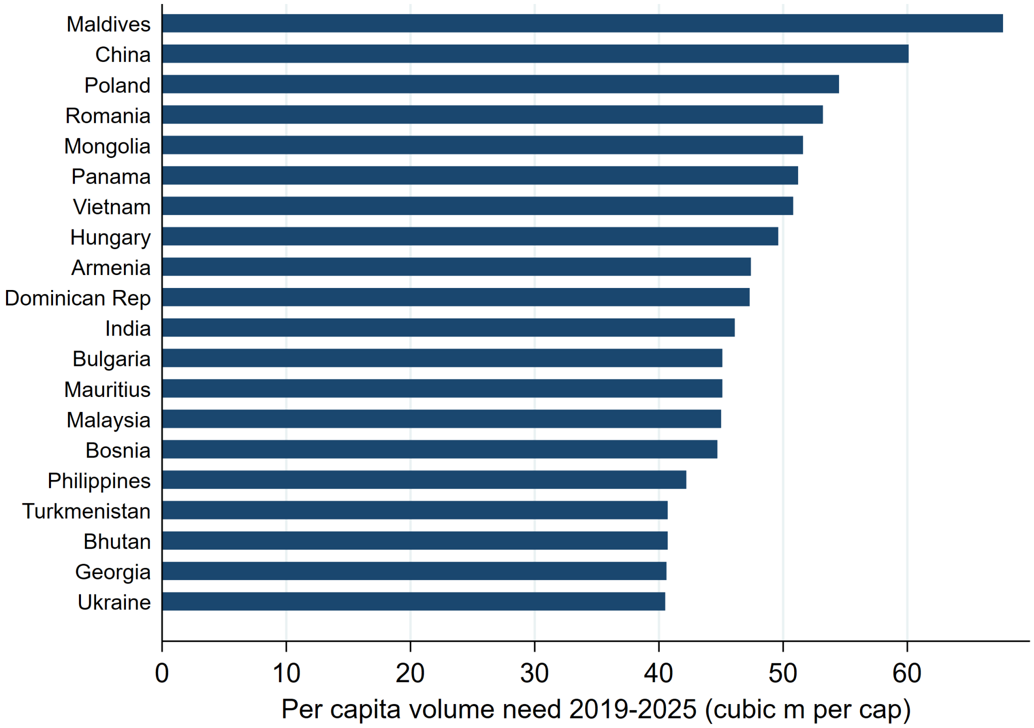
[5] The COVID-19 pandemic could reduce construction needs by increasing mortality and depressing economic growth. However, the remote work revolution has dramatically increased housing demand.

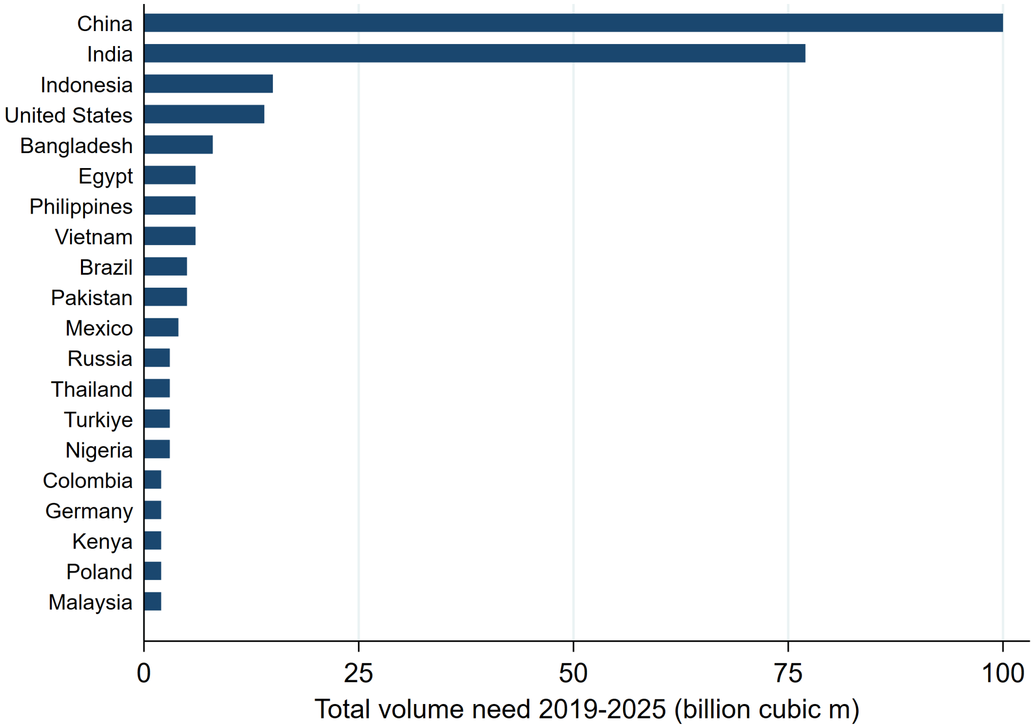
GDP/Population is changing between 2019 and 2025. Likewise, given that we know how population is predicted to change by 2025, we obtain the total volume change needed.

Figure 7: Potential Future Construction Needs, Top 20 Economies, 2019-2025.

(a) Potential Future Per Capita Volume Needs (Cubic m per capita)



(b) Potential Future Total Volume Needs (Billion cubic m)



Notes: The bottom panel and the top panel show the top 20 economies in terms of future predicted per capita construction needs (m^3 per cap.) and total construction needs (m^3) between the years 2019 and 2025, respectively.

Figure 7 lists the top 20 economies in terms of future, growth-driven construction needs. In per capita terms, the list includes fast-growing economies in Asia (China, Viet Nam and India), Eastern Europe (Poland, Romania and Hungary) and Latin America (Panama and the Dominican Republic). Focusing on total volume, China, India, Indonesia, Bangladesh, the Philippines and Viet Nam dominate the list. LICs are missing from the list because they were not as of 2019 forecasted to grow fast in terms of per capita GDP, or at least not fast enough to allow enough of these nations to pass the cut-off at which volumes per capita increase with incomes.

Developing Asia accounts for 77% of future global construction needs vs. 8% for Africa and 5% for Latin America. China alone might need to build 100 billion m^3 (3% of its current stock). Given their high income growth *and* population growth, India and Indonesia might need to increase their current stock by 8% (77 billion m^3) and 6% (15 billion m^3), respectively. In both countries, the effects of fast income growth and fast population growth compound each other. Other large economies with significant future needs are Bangladesh (14% of its current stock), the Philippines (10%), Egypt (5%), Viet Nam (5%), and Pakistan (4%). In contrast, the U.S. might need to increase its stock by 1% only. However, that is high in absolute terms (14 billion m^3 in the U.S. vs. 15 billion m^3 in Indonesia), since the U.S. has a large building stock to start with.

Noticeably, the rankings are barely affected if we only consider the effects of income growth (not shown). That is because income growth is what is driving future construction in that exercise. Indeed, countries with the highest population growth rates today are low-income countries characterized by sluggish income growth rates. In addition, given the non-linearities seen in Figure 4, economic growth may not increase per capita volumes for LICs and LMICs.

Lastly, meeting the predicted needs would increase global carbon emissions by $\sim$8%.

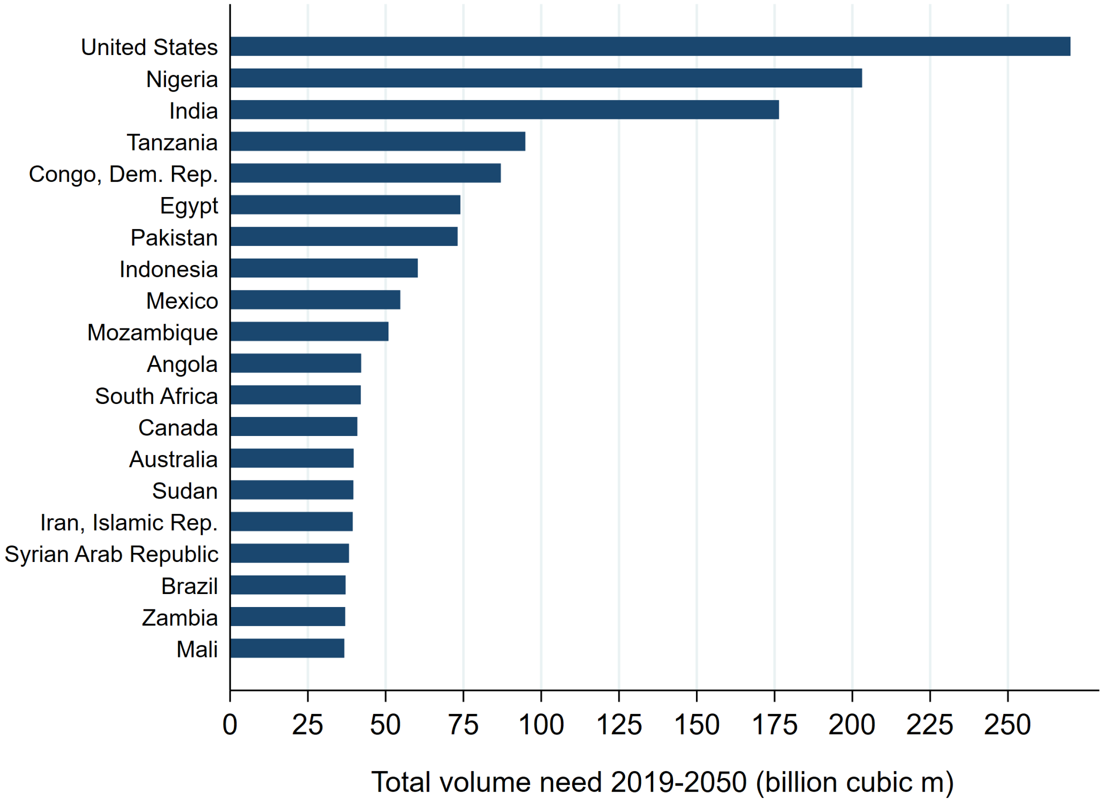
4.3.2. Forecast until 2050

We obtain each country's predicted population in 2050 (United Nations, 2019) and predict total construction needs by 2050. Not knowing future incomes, we cannot forecast construction needs per capita. We also ignore any potential impact of population growth/decline on per capita incomes, hence per capita volumes (which we take as given as of 2019). Figure 8 lists the top 20 economies in total needs. It includes many African LICs and LMICs with fast population growth (Nigeria, Tanzania, the Democratic Republic of Congo, and Mozambique). However, the list also includes LMICs and UMICs whose population is not growing as fast but whose volume per capita is higher given the higher incomes there (India, Egypt, Indonesia, and Mexico). Finally, the list includes developed economies with non-nil population growth and high volumes per capita (U.S., Canada, and Australia). Thus, population growth has larger effects when average consumption levels are higher, which may offset the fact that richer nations have slow population growth.

Africa, predicted to account for 58% of global population growth by 2050, now makes up 48% of future global construction needs vs. 26% for developing Asia (7% for developing LAC). Meeting global predicted needs would then increase global carbon emissions by ∼63%.

To conclude, given its current levels of economic underdevelopment, Africa's current gap is much smaller than Asia's gap. However, Africa will need to build much more dramatically than Asia in the coming decades in order to accommodate its faster-growing population.

Figure 8: Potential Future Construction Needs, Top 20 Economies, 2019-2050.



Notes: The figure shows the top 20 economies in terms of future predicted total construction needs (m^3) between the years 2019 and 2050. These estimates are based on forecasted population growth 2019-2050 alone.

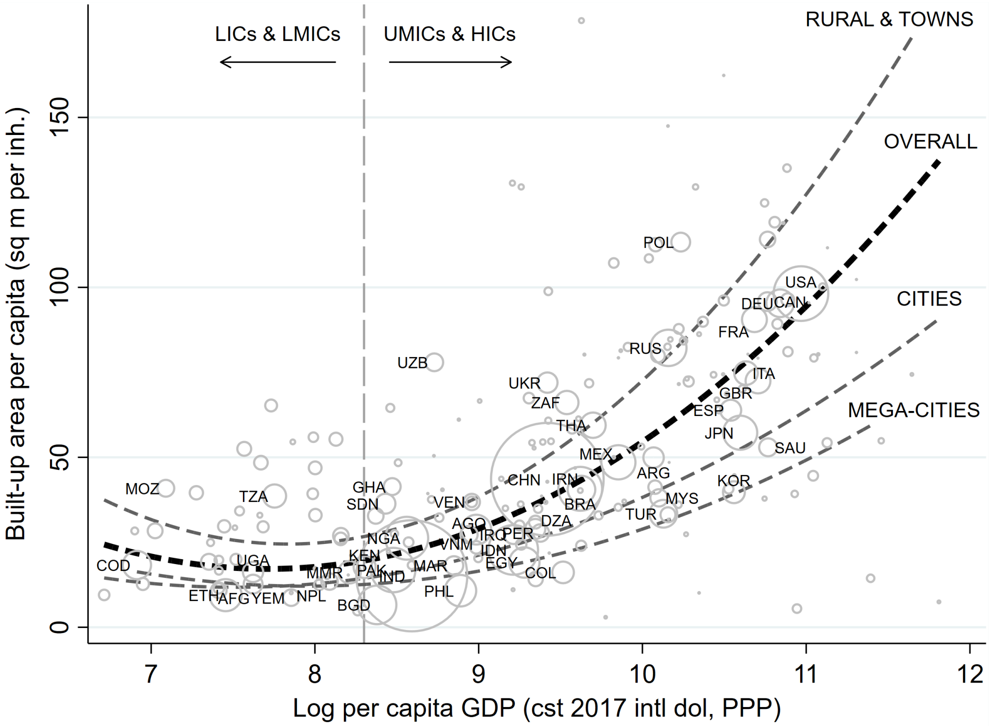
5. Outward versus Upward Construction

We now use the WSF3Dv2 data to unpack how outward construction and upward construction account for the volume-income relation observed globally.

5.1. Decomposition of International Volume Differences

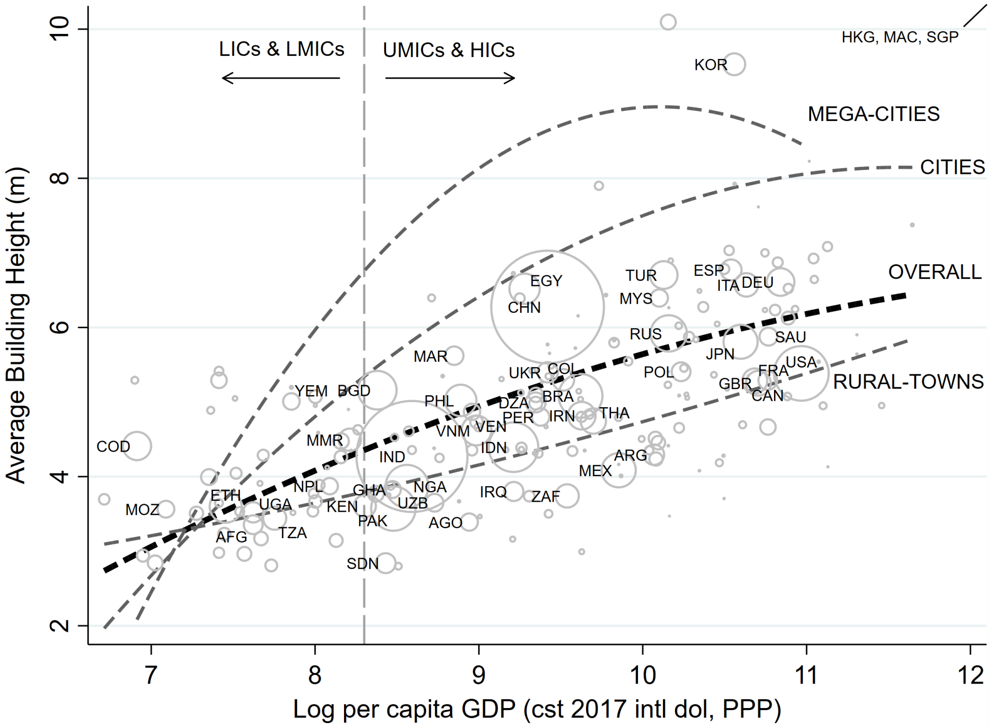
Figures 9 and 10 show the equivalent relation with respect to per capita income as in Figure 4 but for built-up area per capita (m^2) and average height (m) (see the "Overall" line). The relationship is convex for built-up area. The average resident in LICs, LMICs, UMICs, and HICs occupies 22, 21, 44, and 80m^2 of built-up area, respectively. The relationship is then more linear for average height. Average height in LICs, LMICs, UMICs, and HICs is 3.8, 4.3, 5.6, and 6.2 m respectively. Richer nations build systematically more, both horizontally and vertically.

Figure 9: Total Building Area per Capita and Economic Development, 2010s.



This figure shows for 204 countries the relation between total built-up area per capita in 2012/2019 (m^2 per inh.) and log mean per capita GDP in 2010-19 (PPP terms and cst 2017 intl dollars). We use country pop. in 2019 as weights.

Figure 10: Average Building Height and Economic Development, 2010s.

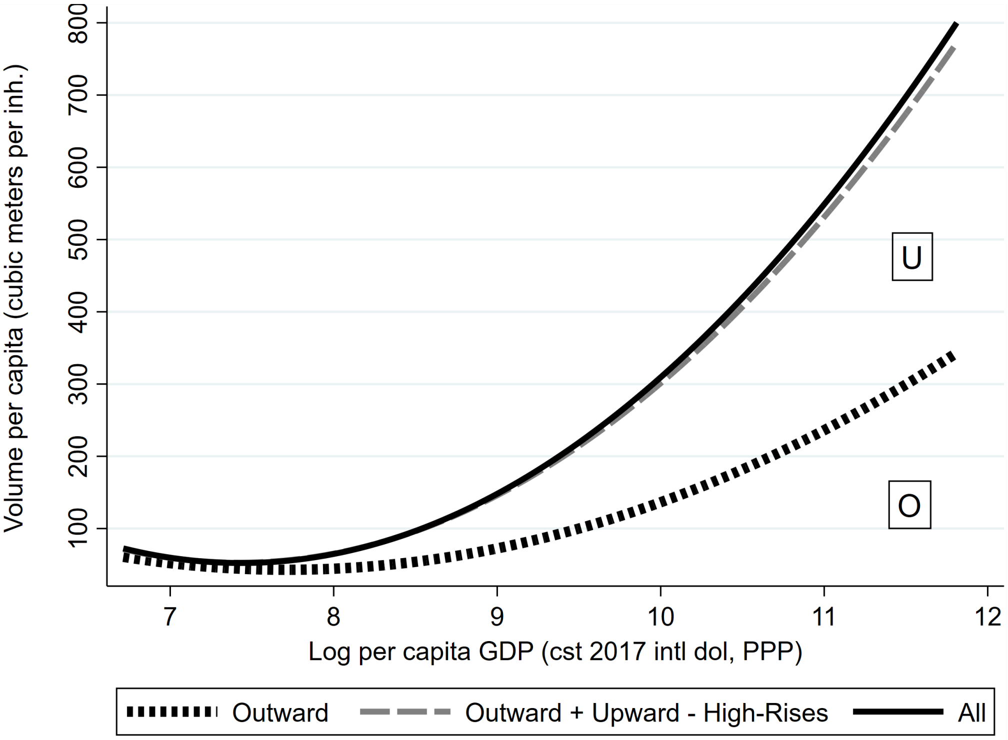


This figure shows for 204 countries the relation between average building height in 2012/2019 (m) and log mean per capita GDP in 2010-19 (PPP terms and cst 2017 intl dollars). We use country pop. in 2019 as weights.

To obtain the overall contributions of verticality and horizontality to international volume differences, we examine how the volume-income relation is explained by outward volumes (building areas x 2.5m, or volume provided by the first floor of each building) and upward volumes (total volumes minus outward volumes, or volume added by additional floors).

The solid line in Figure 11 shows the relation between volume per capita and log per capita GDP from Figure 4. The other lines show the relation with respect to income when considering outward volume (dotted line) or total volume minus volume from high-rises (dashed line). Area O represents the contribution of outward volume to international volume differences. The contribution of upward volume can be approximated by area U, with low-rises driving this contribution (since including high-rises barely changes U). Visually, U exceeds O.

Figure 11: Total Building Volume Per Capita and Economic Development, 2010s.



This figure shows for 204 countries the relation between log mean per capita GDP in 2010-2019 (in PPP terms and cstt 2017 intl dollars) and different measures of volume per capita in 2012/2019 (m^3 per inh.): (i) Outward: outward volume per capita; (ii) Total excl. high-rises (HRs): total volume per capita when including outward volume + upward volume provided by low-rises; and (iii) Incl. HRs: total volume per capita when including outward volume + upward volume provided by both low-rises and high-rises. We use country populations in 2019 as weights.

Indeed, using econometric regressions wherein the dependent variable is the unlogged per capita volume and the independent variable is log mean per capita GDP, the following coefficients for total, outward and upward volumes (N=204) are obtained: 112***, 40*** and 73***, respectively (138***, 53*** and 85*** with population weights). Changes in areas and heights thus explain (40 / 112 ≈) 35% and (73 / 112 ≈) 65% of total volume differences, respectively. In developing economies, changes in areas and heights similarly explain ∼40% and ∼60% of total volume differences, respectively. Therefore, vertical expansion is the main driver of international volume differences, both globally and in the developing world.

Low-rises and high-rises account for 93% and 7% of the upward volume-income relation, hence 60% and 5% of the total volume-income relation (we find similar patterns in developing economies). The volume added by high-rises is only 2%-3% in LAC and Asia and 0% in Africa (Table 1). While high-rises may visually appear as driving verticality globally, low-rises (<50m) dominate construction patterns worldwide. This suggests that policies constraining low-rise development are more consequential than policies related to land expansion or high-rise development. Also, low-rises have the added advantage that they are more likely to house the middle-class, whereas high-rises may more specifically cater to the needs of the wealthy.

Lastly, LAC and Asian buildings both provide ∼50% more volume per capita than African buildings. However, LAC does so by providing more outward volume (+30% than Africa vs. +1% for Asia) whereas Asia uses more upward volume (+125% than Africa vs. +105% for LAC). The fact that world regions use various ways to provide space to their residents leads us in the next subsection to study the upward vs. outward specialization of countries and regions. Note that this specialization is obtained conditional on income, and thus does not address the role of the development process in construction. Instead, it asks, how is the space of a country provided relative to other countries with similar income levels. Policy-wise, this informs us on the type of settlements found in a country, which has economic, social, and environmental implications because outward expansion implies less compact settlements. Outward expansion may then be due to stringent height restrictions and/or public investments in transportation infrastructure (since lower commuting costs in a locality tend to decentralize its population patterns).

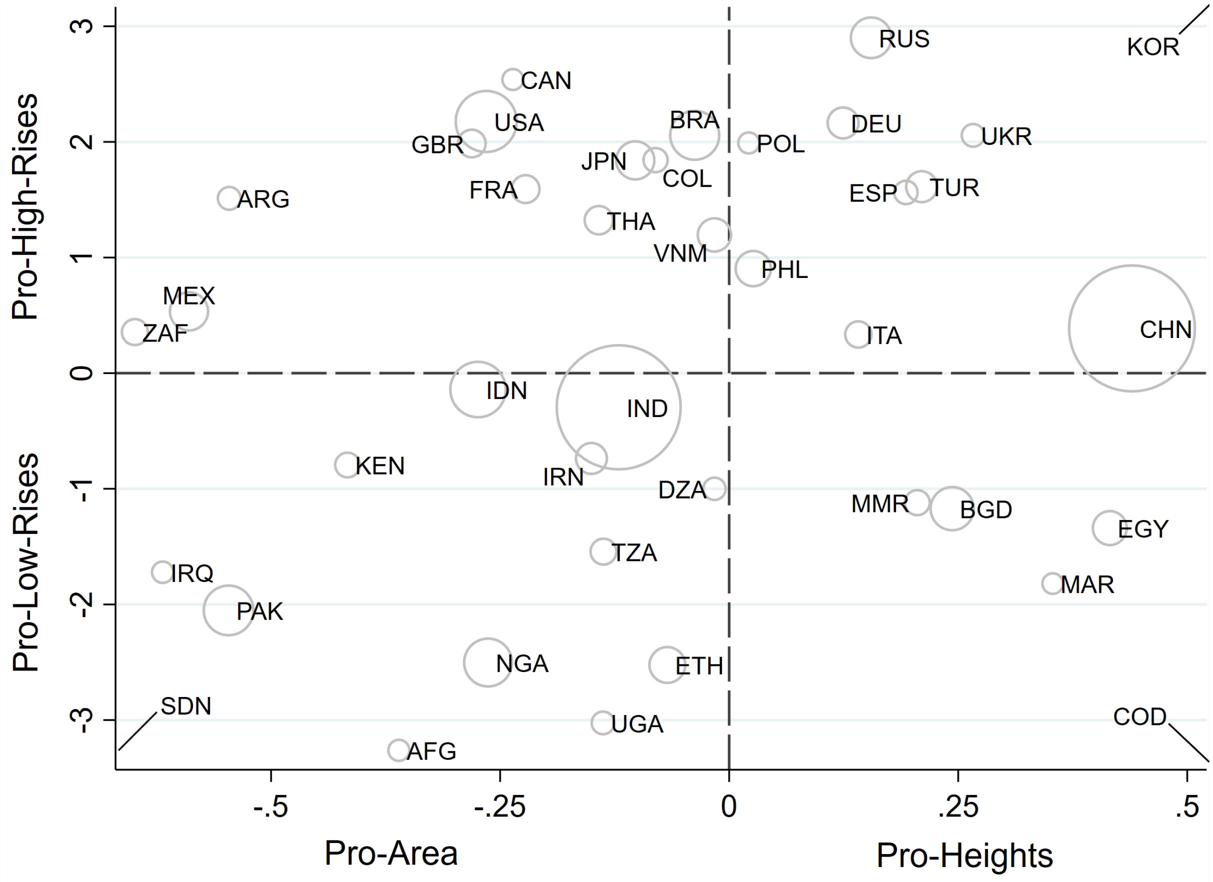
5.2. Upward versus Outward Specializations

We proceed in several steps for this analysis. First, outward volumes are residualized with respect to log per capita income, capturing whether a country provides a lot of area per capita given its income level. Second, upward volumes are residualized with respect to log per capita income, capturing whether a country provides a lot of height per capita given its income level. Overall, countries with higher area residuals have higher heights residuals (countries with “good” areas have “good” heights). Third, the upward volume residuals are residualized with respect to the outward volume residuals, with the resulting residuals indicating how relatively more pro-heights or pro-area the country is, given its income level and other similar countries’ specializations. Fourth, the final residuals that we estimate indicate whether a country is relatively pro-high-rises or pro-low-rises for a given income level (using the same procedure as for areas and overall heights). See Appx. Section C1. for details on these procedures.

Figure 12 plots the pro-high-rises/low-rises residuals against the pro-heights/area residuals. Nations in Asia (China and the Republic of Korea), Eastern Europe (Poland and the Russian

Federation), Western Europe (Germany and Spain), and the Middle East (Türkiye), for example, show a stronger tendency to build upwards *and* build high-rises (top-right quadrant). Few economies build upwards *and* prefer building low-rises when doing so (Bangladesh and Egypt) (bottom-right quadrant).

Figure 12: Classification of Countries: Area vs. Heights, 2012/2019.

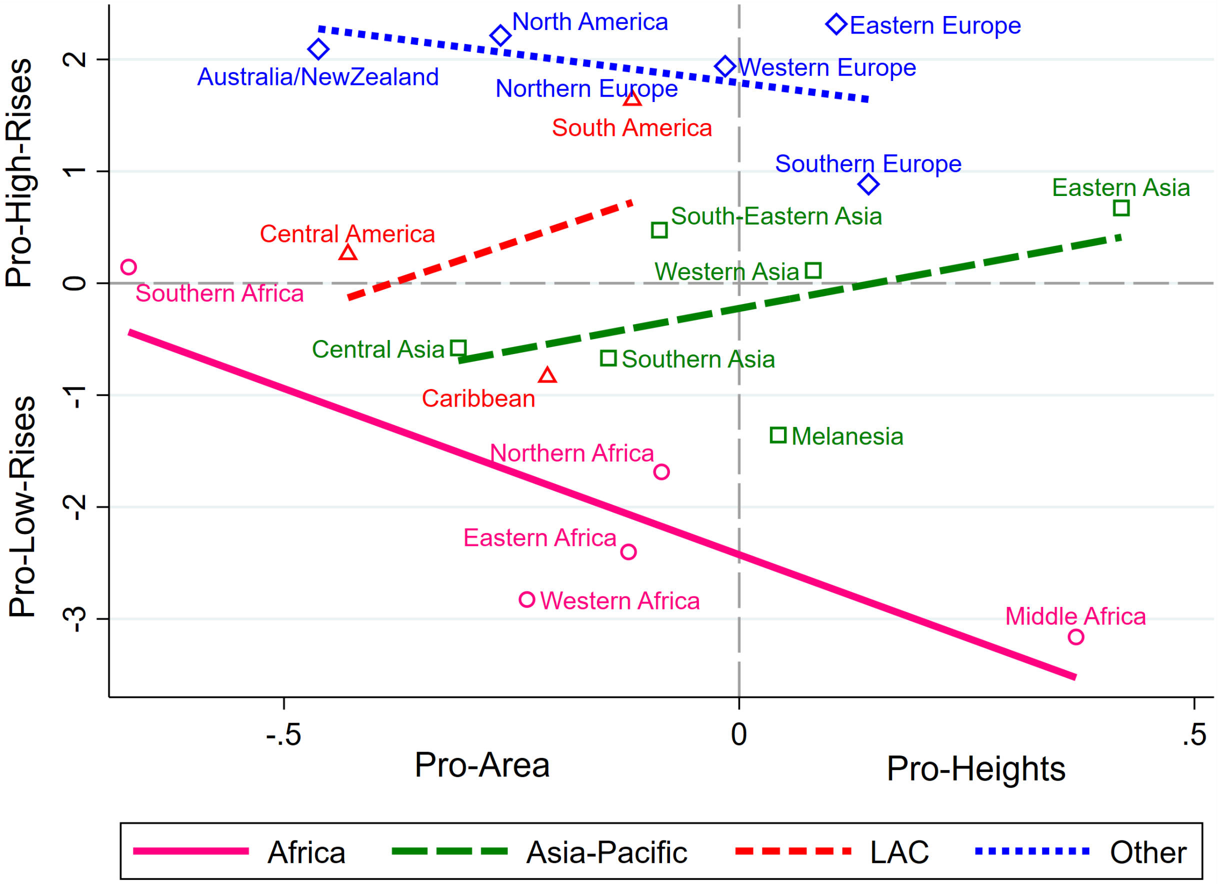


Notes: The plot shows for the 40 most populated countries in the world today the relation between the pro-heights residuals and the pro-high-rises residuals (high-rises: buildings >50m) in 2012/2019. The size of the bubbles indicates the countries' populations in 2019. See text for details on how the residuals are estimated.

Conversely, countries that are better at building outwards, which, when building upwards, tend to build high rises (top-left quadrant), are largely "suburban" nations where some cities have large building stocks (the U.S., Canada, and South Africa) and countries comprising of flat cities and vertical "islands" (France, the UK, Argentina, and Mexico). Brazil, Colombia, Japan, and Viet Nam are in-between. Countries better at building outwards, but which build low-rises when building upwards (bottom-left quadrant), include some nations in the Middle East (the Islamic Republic of Iran and Iraq), South and South-Eastern Asia (India, Indonesia, and Pakistan), and Africa (Ethiopia and Nigeria).

Figure 13 shows the classification for the 20 U.N. subregions. There is clear clustering with Asia being overall more pro-heights than other regions, and most Asian subregions being neither pro-high-rises nor pro-low-rises, suggesting tall settlements with a balanced height distribution. LAC subregions are pro-area, and its two largest subregions are pro-heights (South and Central America). Almost all African subregions are pro-area and pro-low-rises, suggesting flat settlements. Developed regions are mostly pro-area, but pro-high-rises for their heights.

Figure 13: Classification of UN Subregions: Area vs. Heights, 2012/2019.



Notes: This figure shows for 20 U.N. subregions the relation between the pro-heights/pro-area residuals in 2012/2019 and the pro-high-rises/pro-low-rises residuals in 2012/2019. The lines represent linear fits for each region.

More generally, developing regions tend to be pro-area. However, different levels of pro-high-rise preferences can be observed. South America, Central America, Southeast Asia, and Southern Africa are pro-high-rises. Other subregions, especially in Africa, are pro-low-rises. Since African settlements are not particularly known for having extensive transportation networks, it must be that African nations are pro-area and -low-rises because of height restrictions (looser urban containment policies could also contribute to this). Latin American nations are then as pro-area as African nations overall. However, they are more pro-high-rises when building tall, which may suggest looser height restrictions in some of their settlements. Finally, Asian nations being more pro-heights likely suggests looser height restrictions there.

6. The Influence of Urban and Rural Areas as Countries Develop

We just found that upward construction and outward construction respectively account for 60%-65% and 40%-35% of international volume differences, with the contribution of upward construction almost entirely driven by low-rises. Since countries simultaneously urbanize as they develop, and since urban areas differ from rural areas in many dimensions, we investigate how construction patterns depend on urban status. We first show that low-rises and high-rises more strongly explain volume differences across world cities than across countries. This leads us to examine if cities drive international volume differences across countries. However, we find that rural areas and small towns, not cities, disproportionately influence the distribution of volume per capita at a global scale. Medium to small cities, not large cities, then dominate total urban volumes. More generally, we discuss how urbanization is not the primary factor underlying the building stock-income relation observed across countries. Finally, we use our city-level analysis to study the upward vs. outward specializations of selected urban systems and world megacities.

6.1. International Volume Differences across Cities

Our definition of *urban areas* includes 12,831 cities above 50,000 people in 2015 as identified by GHS-UCDB (Florczyk et al., 2019). Therefore, in our analysis, *rural areas* include small towns and villages below 50,000 people in 2015. Table 2 shows selected summary statistics for urban vs. rural areas. Comparing Tables 2 and 1, the volume per capita added by building upward makes a larger difference at the city level than at the country level. For example, upward building accounts for 55% of total city volumes as compared to 48% at the country level.

Similarly to what we found at the country level, city volume per capita increases with city incomes (Appx. Section C2.-C4. and Appx. Fig. C.3).[6] Using the same regression analyses as before, heights explain between two-thirds and three-fourths of the global city volume-income relation (we found 60%-65% at the country level) (Appx. Section C5. and Appx. Fig. C.4-C.6 for the scatterplots). Low-rises and high-rises account for ∼90% and ∼10% of the upward volume-income relation, hence 65% and 10% of the total volume-income relation (25% for areas). At the country level, lower contributions of 60% were found for low-rises and 5% for high-rises. Lastly, we find very similar patterns and differences considering developing economies only.

Hence, upward construction appears relatively more important for cities than for rural areas. Combined with the fact that more developed economies are also more urbanized, this could

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[6] We use the 2015 city GDP data from Chen et al. (2022) who provide high-resolution "real GDP" data (in 2017 dollars) based on (not top-coded) night lights data as reported by the NPP/VIIRS satellite series. While night lights data could capture infrastructure (including electrification) and past economic development in addition to current economic development as infrastructure and urban structures are durable, we use this data in the absence of better data on city incomes for the whole world. Nonetheless, the city-level results should be taken with caution.

explain why upward construction disproportionately explains international volume differences. However, we actually find the opposite as described in the next subsection.

6.2. Volumes from Urban Areas versus Rural Areas

Urban areas account for 48% and 42% of the world's population and volume. Therefore, rural areas comprise 52% of the world's population *but* 58% of the world's volume (Table 2). This is due to cities being more compact, i.e. spatially efficient, than rural areas (193 and 238 m^3 per resident, respectively). That is the case in both developed and developing economies.

If anything, urbanization should reduce aggregate volume consumption per capita. The fact that volumes per capita increase with incomes suggests that forces other than urbanization itself are at play and dominate the urbanization effect. For example, the residents of wealthier nations could consume more space per capita regardless of their type of residence. Another possibility is that rural areas and small towns drive international volume differences.

Figure 4 (p. 12) gives credence to both hypotheses. Space consumption per capita increases with national income in all types of localities. However, rural volume per capita increases more steeply with income than city volume per capita ("rural-towns" line vs. "cities" line). In other words, world cities are more similar to each other than villages and small towns. Using the same regression analysis as before, we find that rural construction and urban construction respectively account for $\sim$60% and $\sim$40% of international volume differences (finding again broadly similar patterns when considering developing economies only).

The U.N. then defines megacities as agglomerations over 10m+ inhabitants (UN, 2017), which leads to 28 megacities being selected. In order to include more cities, we use a 5 million inhabitants cut-off. This selects 71 megacities (including 55 cities in developing economies) that concentrate 24% of the world's total city population, but account for only 22.5% global building volume provided by cities. Thus, cities with 50k to 5m residents provide the remaining 77.5%.

Similarly, volume per capita increases less steeply for megacities than for all cities across different income levels (see Figure 4 on p. 12), which indicates that megacities are more similar to each other than cities overall. Thus, countries' construction patterns differ more in their small and medium-sized cities than in their largest cities. Relatedly, regression analyses suggest that construction in megacities and construction in other cities respectively account for $\sim$40% and $\sim$60% of international urban volume differences (including in developed economies).

To conclude, rural areas, not cities, disproportionately influence the distribution of volume per capita at a global scale. Medium to small cities then actually dominate total urban volumes.

6.3. Decomposition of International Urban and Rural Volume Differences

Similarly to what we do at the country level, we can decompose international volume differences separately for urban and rural areas. Figures 9 and 10 show the respective built area-income

Table 2: Summary statistics for urban areas and rural areas, 2012/2019

Economies	Volume km^3	Per Cap. m^3	% Outward	% Upward	% Low-Rise	% High-Rise
Panel A:	Urban Areas (Defined as Cities $\geq$ 50,000 Inhabitants in 2015)					
World	677	193	44	55	52	3
Developed	232	399	34	65	58	7
Developing	445	152	46	54	51	3
High-Income	232	399	34	65	58	7
Upper-Middle-Inc.	318	243	37	63	59	4
Lower-Middle-Inc.	109	81	51	49	47	2
Low-Income	17	65	63	37	37	0
Africa	54	99	58	41	41	0
Asia	352	165	42	58	55	3
Europe	127	439	30	70	64	6
Latin America & Carib.	56	160	47	53	47	6
North America	82	473	42	59	54	5
Pacific	6	374	45	55	51	4
Panel B:	Rural Areas (Defined as Villages and Towns $\geq$ 50,000 Inhabitants in 2015)					
World	916	238	60	40	40	0
Developed	343	552	50	51	50	1
Developing	572	177	62	38	38	0
High-Income	343	552	50	51	50	1
Upper-Middle-Inc.	388	262	54	45	45	0
Lower-Middle-Inc.	145	104	67	32	32	0
Low-Income	38	112	73	27	27	0
Africa	94	147	72	28	28	0
Asia	398	174	60	40	40	0
Europe	245	540	50	50	49	1
Latin America & Carib.	58	215	61	39	39	0
North America	111	604	50	49	49	0
Pacific	9	417	59	41	41	0

Notes: This table shows summary statistics for four groupings of countries. Developed Status is based on the World Bank (WB)'s classification of countries in 2019 (= high-income economies). Outward volume = built area x 2.5m. Upward volume = volume - outward volume. High-rise volume = from high-rises ($\geq$ 50 m). Low-rise volume = from low-rises (between 2.5m and 50m).

relation and average height-income relation separately for urban areas ("cities") and rural areas ("rural & towns"). As seen, area increases more steeply with economic development for rural areas than for urban areas (incl. megacities). Conversely, average height increases more steeply with economic development for urban areas (incl. megacities) than for rural areas. However, even for rural areas, average height significantly increases with economic development.

When using regression analyses to decompose volumes per capita, we find that upward construction accounts for 70%-75% of the urban volume-income relation (whether in developed or developing economies) and 60% of the rural volume-income relation (50-55% in developing economies). With rural areas explaining 60% of global volume differences, it makes sense that upward construction explains $\sim$60%-65% of global volume differences.

6.4. Upward versus Outward Specializations: Urban and Rural Areas

LAC and Asian cities provide two-thirds more volume per capita than African cities (Table 2). However, LAC cities do so by providing more outward volume, i.e. flat residential areas (+40% than in Africa vs. +4% for Asia), whereas Asian cities provide more upward volume/heights (+139% than in Africa vs. +89% for LAC). This leads us to examine the upward vs. outward specializations (conditional on income) of selected cities, which are interesting in and of themselves as (vertical and horizontal) land use regulations also vary across world cities.

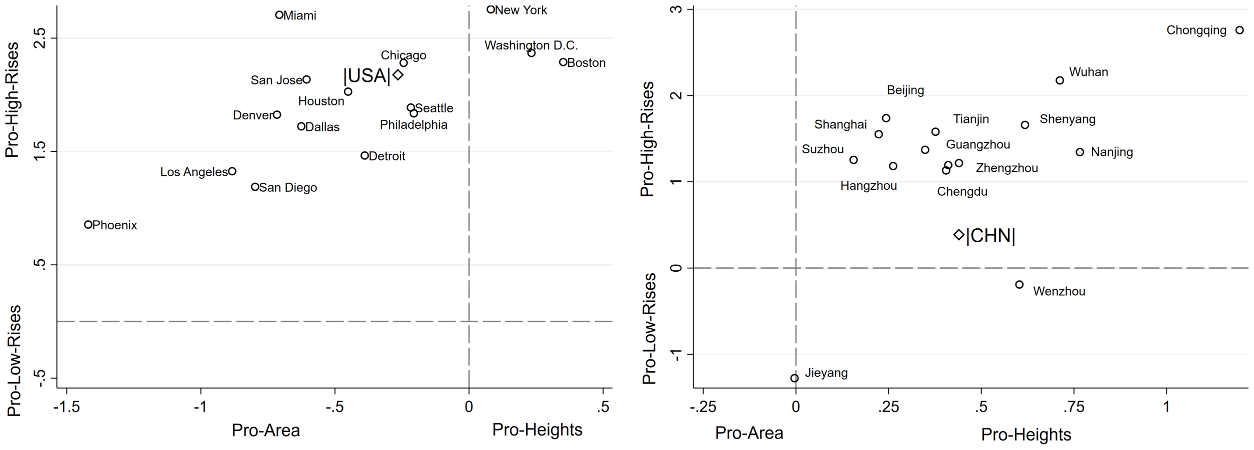
We start with the 12,831 cities using the same residualization procedure as for countries (Appendix Section C6.). Figure 14 shows how the 15 largest cities are classified for six large economies. U.S. megacities are for the most part pro-area (exceptions include New York, Boston, and Washington) and most specialize in high-rises (top-left quadrant). Thus, when U.S. cities build upwards, they are tall. The pro-high-rises and pro-heights residuals are positively correlated, implying pro-height is achieved via high-rises. In contrast, Chinese megacities are clearly pro-heights. Most cities specialize in high-rises (top-right quadrant), and again, a positive relationship between the pro-high-rises and pro-heights residuals is found. Therefore, even if low-rises account for most of the upward volumes globally, high-rises may matter locally.

In India, there are pro-heights cities specialized in high-rises (Mumbai and Bangalore; top-right quadrant), pro-area cities specialized in high-rises for their heights (Delhi and Chennai; top-left quadrant) and pro-area cities specialized in low-rises instead (Ahmedabad and Jaipur; bottom-left quadrant). Brazil is a middle ground between the pro-area U.S. (Rio de Janeiro) and pro-heights China (São Paulo). Most cities specialize in high-rises (top quadrants).

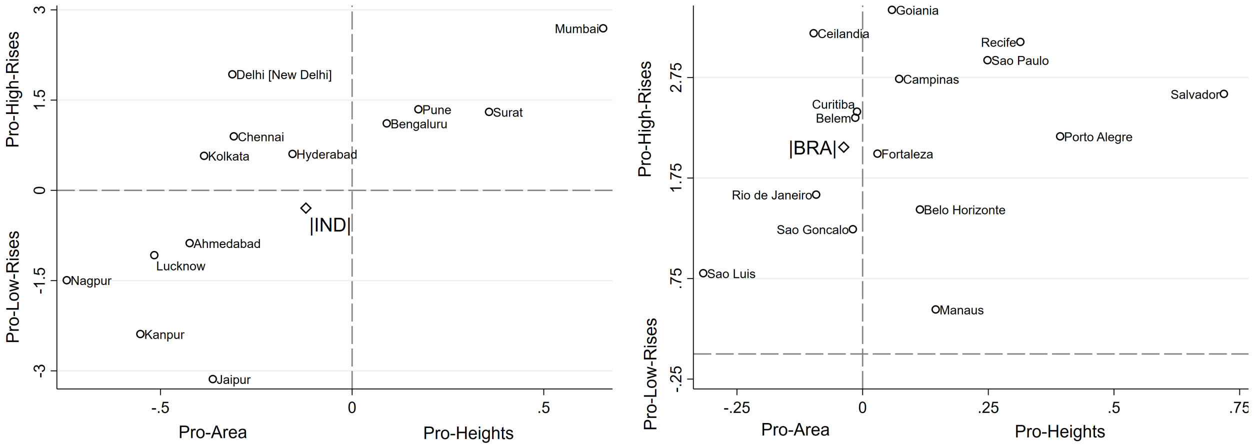
South African megacities are all pro-area and either pro-high-rises (Johannesburg and Cape Town) or pro-low-rises (Port Elizabeth and Polokwane). Nigerian megacities are mostly pro-area. All of them are then pro-low-rises (bottom quadrants). The results show how focusing on a few megacities can generate misleading country classifications. While Mumbai, New York, and São Paulo are pro-heights, large cities in India, the U.S., and Brazil are on average pro-area.

Figure 14: Classification of the 15 Largest Cities in Six Economies, 2012/2019.

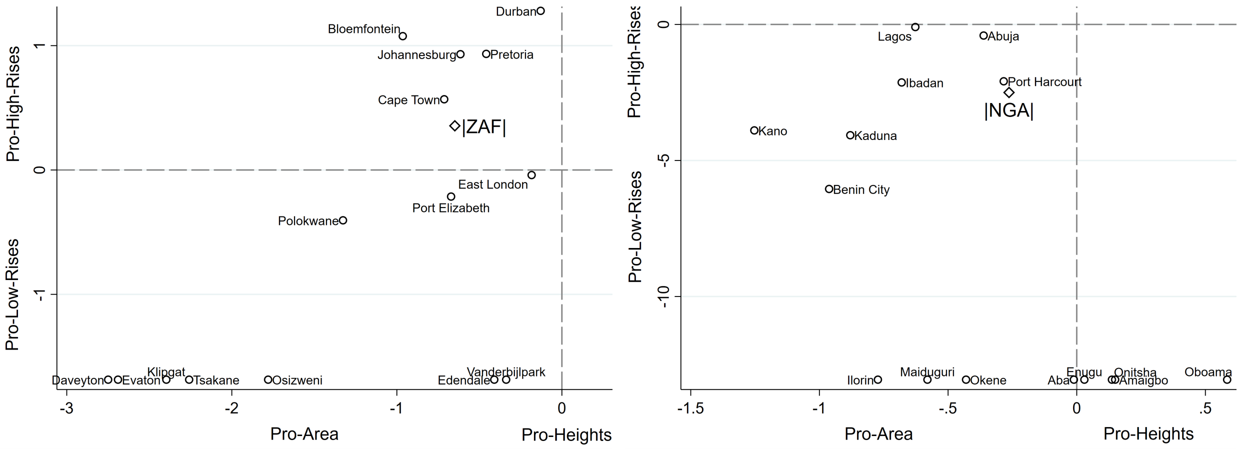
(a) United States (USA) **(b)** China (CHN)



(c) India (IND) **(d)** Brazil (BRA)



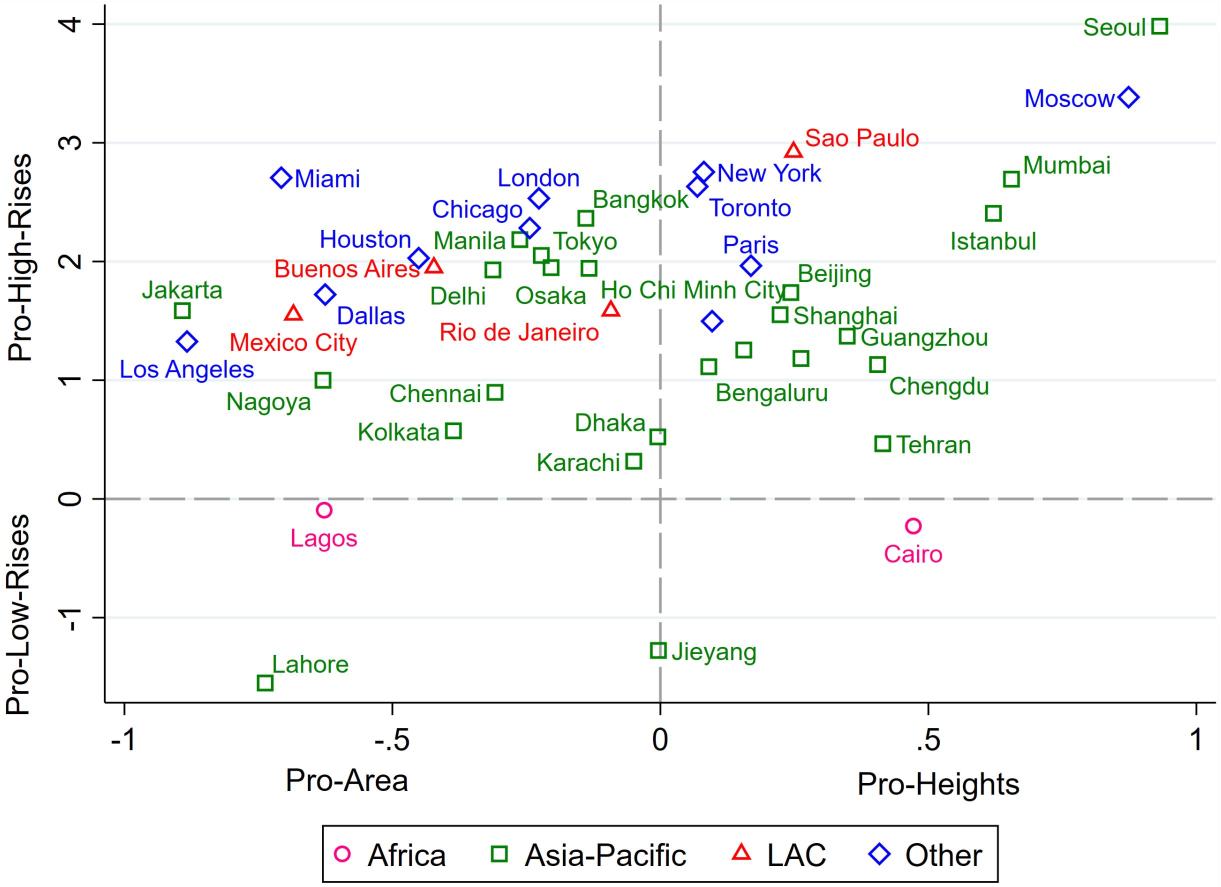
(e) South Africa (ZAF) **(f)** Nigeria (NGA)



Notes: This figure shows for the 15 largest cities (defined in 2015) of six economies the relation between the pro-heights/pro-area residuals in 2012/2019 and the pro-high-rises/pro-low-rises residuals in 2012/2019.

Finally, Figure 15 shows the classification for ∼40 of the largest cities in the world (in GHS-UCDB). The most pro-heights megacities include Seoul, Moscow, Mumbai, Istanbul, and São Paulo, as well as Chinese megacities. Such cities may have less stringent height restrictions (or more stringent urban containment policies). Very pro-area cities are Jakarta, Mexico City, Buenos Aires, Lagos, Lahore and Rio de Janeiro, as well as South Asian megacities (with the exception of Mumbai) and U.S. megacities (with the exception of New York City), possibly to due to more stringent height restrictions (or less stringent urban containment policies).

Figure 15: Classification of the largest cities in the World, 2019.



Notes: This figure shows how 42 large cities (cities among the top 30 in terms of population in 2015 or the top 30 in terms of volume) are classified in terms of the pro-heights residuals and in terms of the pro-high-rises residuals.

Finally, the top 15 cities of all countries account for 55% of city volumes. Appendix Figure C.7-C.9 show the 20 U.N. subregion residuals when considering the top 15 cities, other cities, or rural areas. The residuals are highly correlated with each other (see Appendix Section C6. for details). Regions are thus similarly specialized across-the-board. More generally, nations with sprawling cities also tend to have sprawling rural localities, which suggests an important role for national land use regulation policies (and/or national public transportation investments). Note that it could be that a centralized government imposes such national policies on all localities or that regional/local governments emulate each other in implementing similar policies.

7. Conclusion

Maps have been a major innovation in human history, contributing to nation building and trade globalization. Historically, maps showed the world in 2D. Given historical transportation and building technologies, human life itself was mostly functioning on a horizontal plane. With the advent of airplanes or skyscrapers in cities, our world verticalized. Today, satellite imagery and computer technology allow us to generate a detailed 3D picture of our global built environment.

The outcomes of this global 3D study of the building stock expand the body of research in this area. We have found that economic development accounts for two-thirds of international volume differences, with the remaining third probably due to policy-related factors. While Asian nations have large construction gaps based on current economic conditions, African nations' construction gaps will dramatically increase in the future as the continent keeps experiencing fast population growth. International volume differences are disproportionately driven by upward construction and by rural areas and small towns instead of cities (including rural upward construction). Lastly, nations/cities with similar levels of economic development may specialize in heights or areas. Overall, the results suggest an important role for land-use regulations and highlight that construction patterns may have significant environmental implications.

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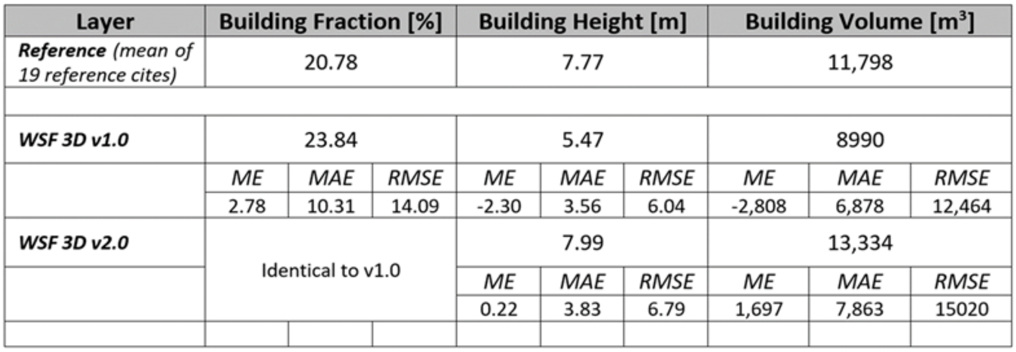
WEB APPENDIX NOT FOR PUBLICATION

A WSF3D VERSION 1 AND WSF3D VERSION 2

Figure A.1 below summarizes the results of a global validation campaign comparing the accuracy of BH and BV in WSF3Dv1 and WSF3Dv2 based on very high-resolution 3D building models (<50 cm, level of detail 1) obtained for 19 globally distributed regions covering a total of 85,878 km^2 (Esch et al., 2022). The data obtained shows that the mean estimation error of the building height BH of -2.3 m in WSF3Dv1 (i.e., underestimation of the actual building height) could be reduced to 0.22 m in the new version WSF3Dv2 by adding Emporis data.

Figure A.1: Validation results of WSF3D version 1 and version 2, 2019.



Layer	Building Fraction [%]			Building Height [m]			Building Volume [m^3]		
Reference *(mean of 19 reference cites)*	20.78			7.77			11,798		
WSF 3D v1.0	23.84			5.47			8990		
	ME	*MAE*	*RMSE*	*ME*	*MAE*	*RMSE*	*ME*	*MAE*	*RMSE*
	2.78	10.31	14.09	-2.30	3.56	6.04	-2,808	6,878	12,464
WSF 3D v2.0	Identical to v1.0			7.99			13,334		
				ME	*MAE*	*RMSE*	*ME*	*MAE*	*RMSE*
				0.22	3.83	6.79	1,697	7,863	15020

Notes: This table shows the validation results of WSF3Dv1 and v2 for the building fraction (BF), building height (BH), and building volume (BV). The error statistics defined for the related 90m products Building Fraction, Building Height, and Building Volume are provided in the form of mean error (ME), mean absolute error (MAE), and root mean square error (RMSE), derived by means of quantitative comparison to reference building models. The accuracies reported for Building Fraction (BF) apply to the building area (BA, Building Area) as well because the latter represent a conversion of the units of measurement from one sphere (here: %) into another (here: m^2).

B Emporis Data

B1. The Emporis Database (EM)

Emporis is a global provider of "international skyscraper and high-rise building data."[1] Emporis relies on information provided by the industry for "thousands of cities worldwide. Emporis collects information about the full life-cycle of each building, from idea to demolition." The full database from 09-07-2022 contains data for 823,061 tall buildings. Note that there is no clear definition of what a tall building is in the Emporis database, but the database contains mostly buildings whose architectural/structural height is above 15 meters.

According to their website, "Emporis collects data on buildings of high public and economic value, connects them with involved companies and sets standards for this information. Our products include Emporis Research, Image Licensing, Premium Company Listing and Online Advertising, and are used by customers from the building industry and other fields. In 2000 the Emporis website was founded as Skyscrapers.com, with a focus on collecting information

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[1] See www.emporis.com/ for details (last accessed 09-07-2022). Although the Emporis community platform was retired on 09-14-2022 when bought by the CoStar group, it can still be accessed through the Wayback Machine.

on skyscrapers and high-rise buildings only. Since 2003 Emporis has branched out, widening its database by collecting building information on all construction types." As such, Emporis obtains data from its extensive member network of land developers, architectural firms, builders, city administrations, and banks to maintain the database. Emporis was recently bought by the CoStar group, a global leader in commercial real estate. As such, the data is confidential.

B2. First-step selection of the tall buildings

We only consider "existing" or "demolished" buildings, thus ignoring "unbuilt" and "planned" buildings. We also exclude "under construction" buildings (as of 09-07-2022) since it means they did not exist as of 2019. This leaves us with 781,136 buildings. Next, we exclude buildings without geographical coordinates. This reduces the sample size to 764,343 buildings. Lastly, we exclude buildings for which we do not have any height information, which further reduces sample size to 748,651 tall buildings.

The main types of tall buildings are "high-rise buildings," "low-rise buildings," "skyscrapers," and "building with towers." Altogether, they account for 96% of buildings and almost 100% of total heights in the data. Other types of buildings include, for example, airport towers, open-air structures, reactor buildings, and telecommunications towers. We do not exclude these as the satellite data that we also use cannot distinguish a building's use. To be consistent with this other data set, we thus keep all buildings, noting that it should not be too consequential for the analysis given how little they contribute to overall heights globally.

B3. Height variables used

The main height variable used by Emporis is "architectural height" (meters), which "is the elevation from its base to its highest architectural element." For some buildings where the information is missing, Emporis reports "architectural height (estimated)," which "is an automatic calculation of a probable approximation" of the architectural height based on other sources of height information and considering the building's locality. Combining both variables, architectural height (incl. estimated) is only missing for 9,151 out of the 748,651 buildings. In contrast, the variable that we are most interested in is "roof height," which is "the vertical elevation from the base of a building to the highest exterior portion of the shell enclosing its interior space." Indeed, this type of height matches the most with what the satellite data captures. As such, it excludes spires and antennas, which do not occupy much volume. Roof height is missing for 724,655 of the 748,651 buildings. However, we can use "architectural height" (i.e., not including the observations for which we have "architectural height estimated" only) to recreate roof height since the two are very correlated with each other (additionally, almost all buildings do not have spires/antennas). More precisely, the coefficient of correlation between the two types of heights is 0.99 (N = 22,396). Next, to impute roof height based on architectural height, we use the following model for buildings b in locality c (N = 23,558):

$$ROOFHEIGHT_{bc} = \alpha + \beta * ARCHHEIGHT_{bc} + \omega_c + \mu_b c.(B1) \tag{1}$$

Note that we include 1,593 locality fixed effects (ω_c). Hence, the comparison is restricted to buildings within the same locality (the locality fixed effects also control for how measurement error could vary across localities). For buildings that we know architectural heights but not roof height, we can use our estimates of α and β to predict roof height. Note that we obtain that α = 1.54 (significant at 1%) and β = 0.96 (ditto). β being lower than 1.00 makes sense since roof height is by construction lower than architectural height. The adjusted R-squared is 0.99, which shows the predictive power of our imputation method. Doing so, we know roof height (in meters) for 739,938 buildings. It is then still missing for 8,713 buildings.

The next height variable that we can use to impute roof height is "highest occupied floor height," which is "the elevation from a building's base to the top of the floor slab of the highest interior level which contains usable floor space." Its correlation with roof height (including the roof height estimates based on architectural height) is 0.99 (N = 2,532). We then estimate a similar to eq. (B1). We obtain that α = 4.84 (significant at 1%) and β = 1.04 (ditto). The adjusted R-squared is 0.99. This allows us to add 10 buildings. We then proceed similarly with tip height, "the vertical elevation from the base to the highest man-made part of the building, or any fixed attachment thereto, whichever is higher" (correlation with roof height = 0.99). This adds 189 buildings. For the remaining 8,514 tall buildings (out of 748,651) without direct or indirect roof height information, we use the number of floors to predict roof height, as it is available for many buildings. But in order to do that, it is important to first understand the relationship between roof height and the number of floors. To do so for buildings b in localities c, we simply regress roof height on the number of floors while also adding locality fixed effects (ω_c):

$$ROOFHEIGHT_{bc} = \alpha + \beta * NUMFLOORS_{bc} + \omega_c + \mu_{bc}. \tag{2}$$

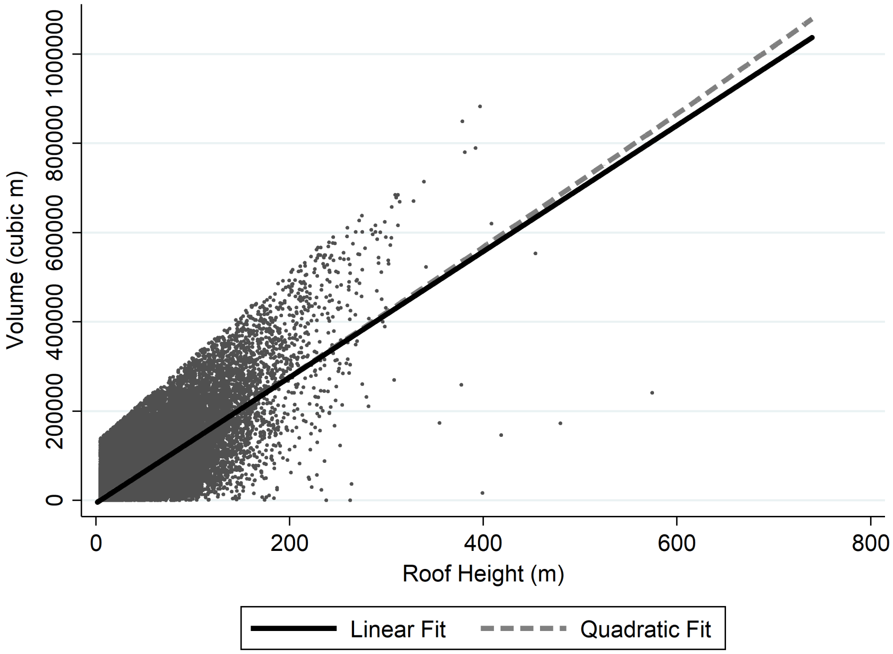
For N = 719,622 buildings, we obtain α = 1.77 (significant at 1%) and β = 3.51 (ditto), implying an average height of about 3.5 m per floor. The adjusted R-squared is 0.98 (the correlation between roof height and the number of floors was also 0.98). Of course, an average height per floor of 3.5 m does not imply that the average ceiling height is 3.5 m (it is typically more around 2.5 m). Lobbies and top floor apartments have tall ceilings. Also, average height per floor includes the space between floors, for example for mechanical, electrical, and plumbing systems. This relationship is also shown visually in Appendix Section B Figure B.1 below.

In the data, most tall buildings in the world are less than 100 m tall in terms of roof height (the 95th percentile is about 110 m). As seen, the relationship is mostly linear. Indeed, below 100 m, the linear and quadratic fits are barely distinguishable. Another way to examine the linearity of the relationship between roof height and the number of floors is to estimate eq. (B2) for different segments of the building height distribution. More precisely, for buildings below 35 m, buildings between 35 and 100 m, and buildings above 100 m, we find a β of 3.3, 3.3 and 3.5, respectively. Since the difference is rather minimal (20 cm per floor), and since β = 3.5 for the full sample, we use β = 3.5 (and α = 1.77) to impute roof height when only the number of floors is available. Ultimately, we have 748,640 tall buildings with available height information.

B4. Second-step selection of the tall buildings based on the completion year

We aim to select buildings that existed as of 2019. To do so, we primarily use information on the year of completion of each building. Among the 748,640 tall buildings, 539,455 buildings have information on their year of completion. Among the remaining buildings, 21,299 have information on the year construction started. In order to use information on the year construction started so as to know if the building existed as of 2019, we must first analyze what construction times typically are for tall buildings.

Figure B.1: Relationship Between Roof Height and the Number of Floors.



More precisely, for 95,515 tall buildings with information on both the year construction started and the year construction ended, the 10th percentile, median, mean and 90th percentile value in construction time is 1, 2, 3, and 4 years, respectively. We also investigate how construction times vary with height, by regressing the construction time on six dummies if the building is 50-100, 100-150, 150-200, 200-250, 250-300, or more than 300 m tall as well as locality fixed effects (omitted category: buildings < 50 m). While the average construction time is 2.3 years for 0-50 m-tall buildings, it is 3-4 years for other height categories. However, given that the mean of construction time is 3 years, we also use 3 years when having to decide if a building was completed by 2019. Therefore, we assume that a building whose construction started in 2016 is on average very likely to have been completed by 2019. Likewise, if we know the year of the last renovation was in 2019 or before, it tells us that the building existed in 2019.

Next, some existing buildings are under renovation (as of 2022). For buildings where we know the year of completion and the year of the last renovation, we obtain the distribution of the number of years a building's renovation typically takes place after completion. The 10th percentile, median, mean, and 90th percentile value in this number is 14, 50, 62, and 110 years, respectively. Thus, we expect all buildings under renovation to have been completed by 2019. For other buildings not under renovation and for which we do not have any information on the year of completion, the year construction started, or the year of the last renovation, we assume that they existed as of 2019. Indeed, a building is in the database if we know its geographical coordinates and have an estimate of its height. If any year-related information is missing, it is unlikely that the building was built after 2019. Since this was so recent, the year of construction would have been easy to know. As such, it is likely that their year of construction is missing because it took place some time ago, and it is now difficult to retrieve exact information on it.

Lastly, there are 152 buildings under demolition and 15,664 demolished buildings. For the buildings under demolition (as of 2022), the question is whether they existed as of 2019. To answer this, we obtain for 8,483 already demolished buildings the absolute difference between the year of demolition and the year of completion. The 10th percentile, median, mean, and 90th percentile value in this number is 27, 47, 53, and 90 years, respectively. Thus, we expect buildings under demolition to have been completed by 2019. Now, for the 15,664 demolished buildings, we only keep buildings whose demolition was after 2019. More generally, for "2019", we keep:

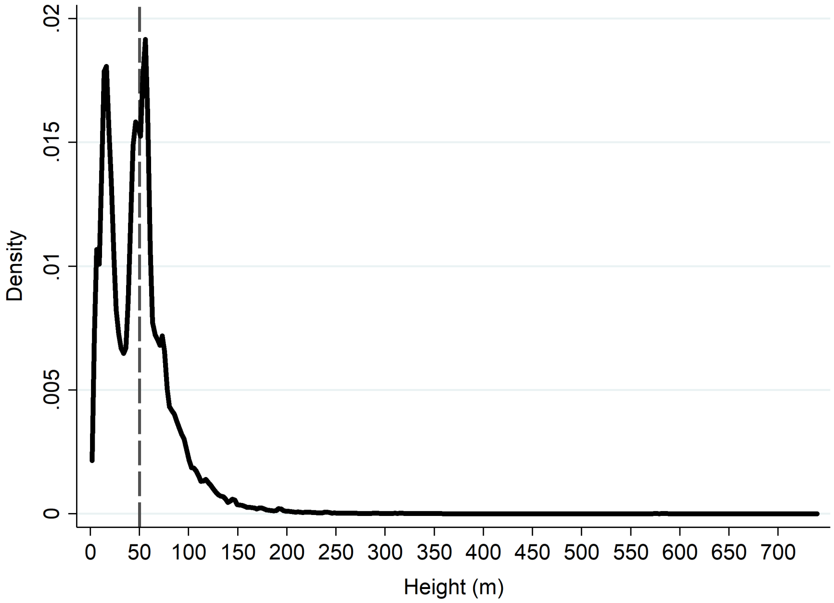
- buildings that were completed by 2019 based on their year of completion
- buildings that were likely completed by 2019 based on the year construction started
- buildings that were likely completed by 2019 based on the year of their last renovation
- buildings under renovation as of 2022
- buildings under demolition as of 2022
- demolished buildings that were demolished after 2019

Ultimately, we will select 711,448 buildings for the year 2019.

B5. Representativeness of the tall buildings data

The cleaned database consists of 711,448 buildings. We now study the Kernel distribution of heights in the data. Appendix Section B Figure B.2 shows the distribution for the whole world.

Figure B.2: Kernel Distribution of Tall Building Heights, the World, Full Sample.



The mode of the distribution is about 50 m (about 14 floors). Since countries are likely to have more buildings below 50 m than above 50 m, and since the distribution of buildings is smooth after 50 m, this suggests that the data set mostly captures buildings above 50 m. Thus, the data set is likely less reliable for buildings below 50 m. Given that the satellite-based data that we use should capture buildings up to 50 m, we believe that we still capture most of the buildings in the world when combining the two datasets. Nonetheless, we can investigate if some regions of the world might have better data. Comparing the six continents (as defined by the United Nations), the mode is around 45-50 m for Africa, 50-55 m for Asia, 40-45 m for Europe, 15 m for North America, 45 m in Oceania and 45 m in South America. Therefore, we are confident that we can use information from the Emporis database to update WSF3Dv1 and create WSF3Dv2.

C Methods

C1. Classifying countries into 4 groups: heights vs. areas, high-rises vs. low-rises

First of all, we “residualize” the log of the outward based volume per capita (i.e., built-up area x 2.5 meters) with respect to log per capita GDP and its square (using country population as weights). As such, the residuals that we obtain capture to what extent a country uses a lot of area per capita given its income level, i.e., relative to the world’s quadratic fit. In layman’s terms, we obtain for each country the absolute distance from the country’s value to the world’s relation. A positive (negative) value implies more (less) outward volume per capita relative to the world.

Second, we similarly residualize the log of the upward volume per capita (= total volume - outward volume). The resulting residuals capture to what extent a country has a lot of (low-rise + high-rise) heights per capita given its income level. In layman’s terms, we obtain for each country the absolute distance from the country’s value to the world’s relation. A positive (negative) value implies more (less) upward volume per capita relative to the world.

Third, countries with higher area residuals tend to have higher heights residuals (correlation ≈ 0.7), implying that countries that are “good” in one dimension are also “good” in the other dimension. However, since we are interested in the comparative rather than absolute advantage of each country, we residualize the height residuals with respect to the area residuals (using country populations as weights). In layman’s terms, we obtain for each country the distance from the country’s value to the world’s relation. A positive (negative) value implies more (less) heights per capita (rather than area per capita) relative to the world. The final residuals thus indicate to what extent a country is relatively pro-height or pro-area for a given income level.

We proceed likewise for high-rises vs. low-rises, first residualizing high-rise and low-rise volumes with respect to income, then residualizing the high-rise residuals with respect to the low-rise residuals. The final residuals indicate to what extent a country is relatively pro-high-rises rather than relatively pro-low-rises for a given income level.

C2. Relation between city economic development and city building stocks

To study how city building stocks vary with income, we use the 2015 city GDP data of Zhou et al. (2022) who provide “real GDP” data (2017 dollars) based on unbounded night lights data. We use this data in the absence of global city income data. City GDP is total lights within a UC boundary.

Finally, log(city GDP) / log (city pop.) is our income measure instead of log (city GDP / city pop.). We believe that the latter measure does not properly capture city incomes due to non-linearities in the relation between lights and population (see Appendix Section C3. below).

Appendix Figure C.3 shows a positive volume-income relation. For a given income level, there is more variation across cities than across countries. For example, volume per capita dramatically varies across U.S. cities despite them having similar incomes when compared to other world cities (e.g., 311m^3 per resident in New York vs. 569 in Dallas).

Note that this analysis indirectly controls for the effect of city population size. In the U.S., city incomes and sizes strongly correlate (Appendix Fig. C.5). That is also true globally conditional on country indicator variables (see Appendix Section C4. below). Indeed, within the same economy, higher-wage cities attract workers. Conversely, larger cities are denser, which generates productivity-enhancing agglomeration economies (Combes and Gobillon, 2015).

Based on the same analysis as at the country level, heights explain between two thirds and three fourths of the volume-income relation (vs. 65% at the country level) (Appx. Section C5. and Appx. Fig. C.4-C.6). Low-rises and high-rises account for 88% and 12% of the heights-income relation, hence 65% and 10% of the volume-income relation (25% for areas). At the country level and including rural areas, we found 60% for high-rises, 5% for low-rises, and 35% for areas.

C3. City per capita income measure

To study how city stocks vary with respect to income, we use the 2015 city GDP data from Chen et al. (2022). More precisely, they provide high-resolution "real GDP" data (in 2017 dollars) based on (not top-coded) night lights data as reported by the NPP/VIIRS satellite series. While night lights data could capture infrastructure (including electrification) and past economic development in addition to current economic development as infrastructure and urban structures are durable, we use this data in the absence of better data on city incomes for the whole world. To obtain a measure of city GDP, we rely on the total sum of lights within each city's boundary as defined by GHS-UCDB (Florczyk et al., 2019). Finally, we use log(city GDP) / log (city pop.) as our city per capita income measure instead of log (city GDP / city pop.).

Indeed, the latter measure does not, in our view, properly capture city incomes due to non-linearities in the relationship between lights and population. As shown for 324 U.S. metro areas in Appendix Figure C.5, log (city GDP / city pop.) decreases with city population size for larger cities, for example due to street lighting being a non-rivalrous good. Indeed, the use of street lighting by some individuals does not diminish its availability to other individuals. As such, the number of street lights per capita should increase less than proportionally with respect to population. There could be of course other reasons. In contrast and as can be seen in Appendix Figure C.5, log (city GDP) / log(city pop.) increases (slightly concavely) with city size.

C4. Relation between city per capita income and city population size

As shown in Appendix Figure C.5 for 324 U.S. metro areas, city per capita incomes and city population sizes are very strongly correlated (correlation about 0.9 and R-squared of 0.90). That is also the case in large countries with many cities, for example China and India (not shown).

Globally, conditional on country indicator variables capturing country-specific factors, we also find that this is the case (correlation about 0.7 and adjusted R-squared of 0.83). Note that we consider 12,516 world (GHS-UCBD) cities in 168 countries for this analysis.

C5. Decomposing built-up volumes at the city level

The higher levels of volume per capita in richer/larger cities are driven by both larger areas and taller buildings in them. To obtain their respective contributions to total volumes, we rely on equation (C4.1) and use simple econometric regressions where the dependent variable is the unlogged per capita volume variable considered and the variable of interest is the per capita income measure based on night lights in 2015 (N = 12,516 world cities).

Total Volume = outward volume (area) + upward volume (heights) (C4.1)

We obtain the following slopes for total volume, outward volume and upward volume: 444***, 152*** and 292***, respectively (*** implies significance at 1%). Using country populations as weights, we get 283***, 74*** and 209***, respectively. The implication of these results is that heights contribute to between two thirds and three fourths of the volume-income relation.

We then obtain the following slopes for upward volumes based on low-rises or high-rises: 281*** (184*** with population weights) and 12*** (25***), respectively. Giving more weight to larger cities since they account for most of the world's urban population, low-rises and high-rises respectively account for 88% and 12% of the heights-income relation, hence 65% and 10% of the volume-income relation (25% for areas). In contrast, at the country level and including rural areas, we found 60% for high-rises, 5% for low-rises, and 35% for areas.

C6. Classifying regions into 4 groups for primate & secondary cities & rural areas

For each subregion, Appx. Fig. C.7-C.9 show the (locality) population-weighted average residuals when only considering large cities (defined as cities in the top 15 of each country), small and medium-sized cities (cities not in the top 15 of each country) or rural areas & towns (localities $<$ 50,000 c. 2015). Comparing the three figures, one can see how some regions exhibit similar patterns for each type of locality. The coefficient of correlation between the pro-height residuals based on large cities and the same residuals but based on small and medium-sized cities or rural areas & towns is $\sim$0.7-0.9. Correlation is less high but still positive, at $\sim$0.45-0.6, for the pro-high-rises residuals. Thus, regions tend to be similarly "specialised" across all localities.

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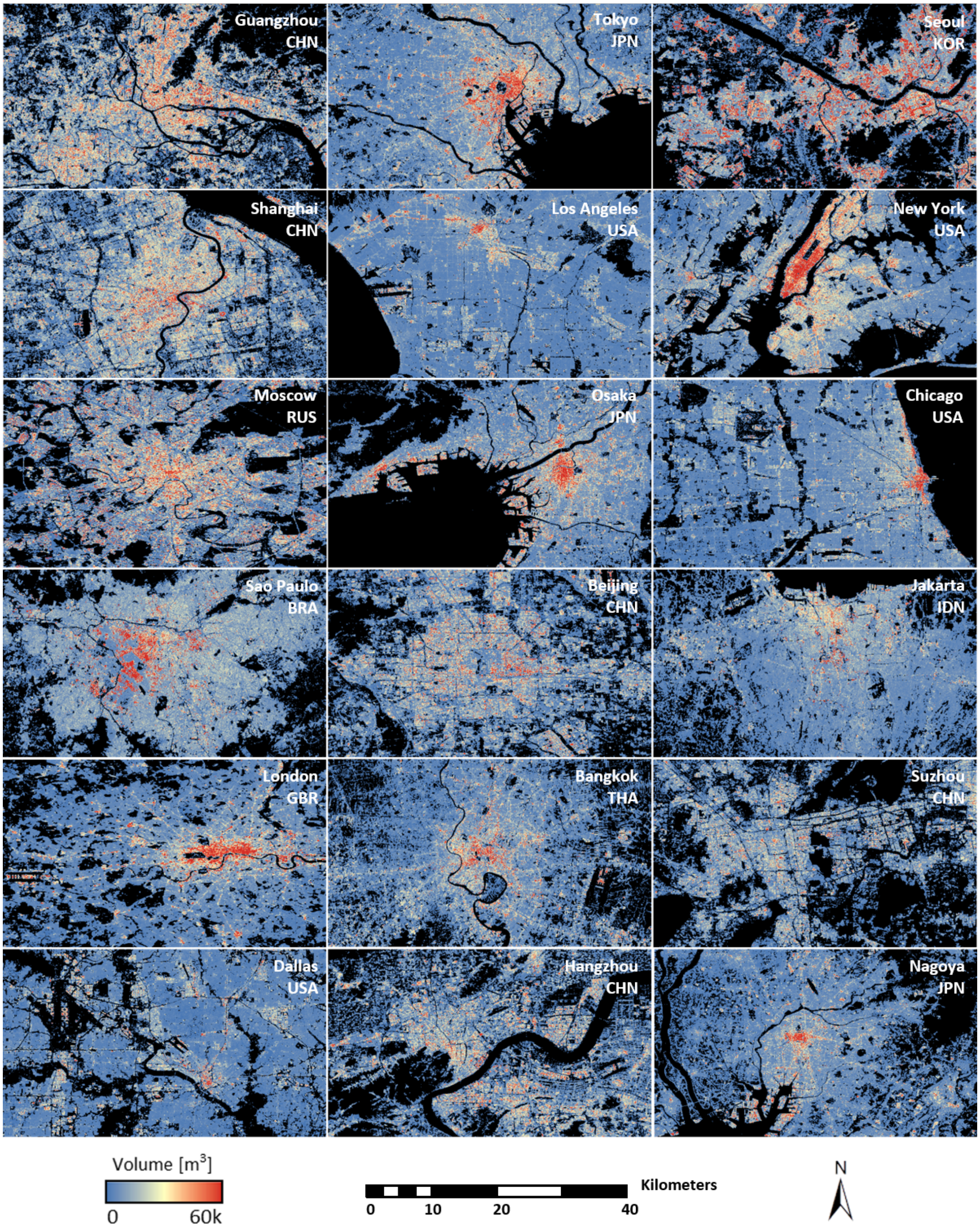
C. Appendix Figures and Appendix Tables (NOT FOR PUBLICATION)

Figure C.1: Built-Up Volume for Selected Urban Agglomerations, 2012/2019.



Notes: The map shows the spatial distribution of building volumes (m^3) as given by WSF3Dv2 (resolution of 90 m).

Figure C.2: Built-Up Volume for the Whole World, 2012/2019.

Notes: The map shows the global spatial distribution of building volumes (m^3) as given by WSF3Dv2 (resolution of 90 m).

Figure C.3: City Volume Per Capita and City Income Per Capita, 2010s.

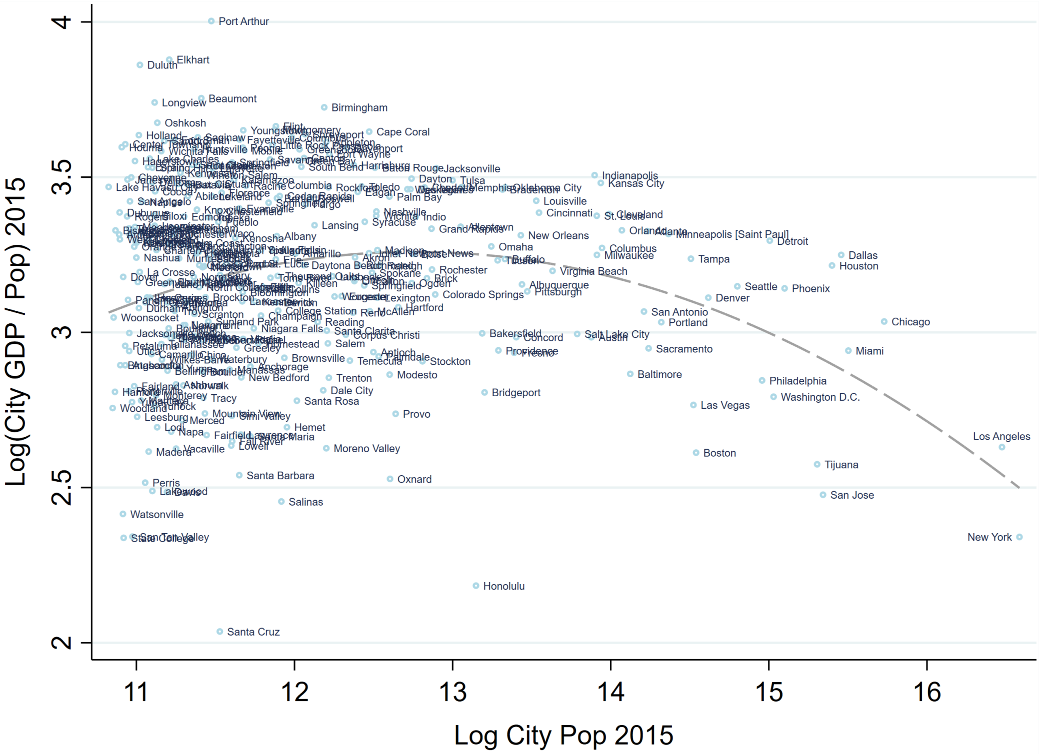
This figure shows the relation between city volume per capita (m3 per inhabitant) in 2019 and log(city real GDP in Bn. 2017 USD) / log (city population) in 2015. The relation between the two is proxied by a fractional polynomial fit (using city pop. in 2015 as weights). We exclude outliers above the 99th percentile value in volume per capita.

Figure C.4: City Total Building Area Per Capita and City Income Per Capita, 2015.

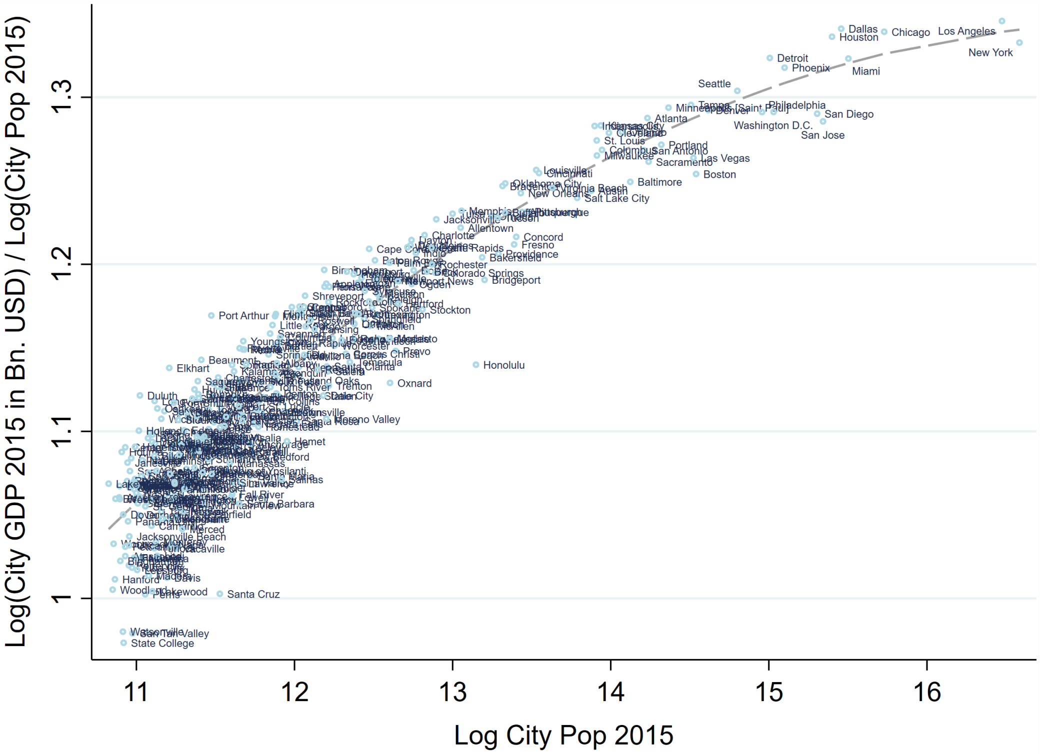
This figure shows the relationship between city area per capita (sq m per inhabitant) in 2019 and log(city real GDP in Bn. 2017 USD) / log (city population) in 2015. The relationship between the two is proxied by a fractional polynomial fit (using city populations as weights). Note that we exclude outliers above the 99th percentile value in area per capita.

Figure C.5: City Per Capita Income and City Population Size, USA, 2015.

(a) Using log(city GDP / city pop.) as the per capita income measure

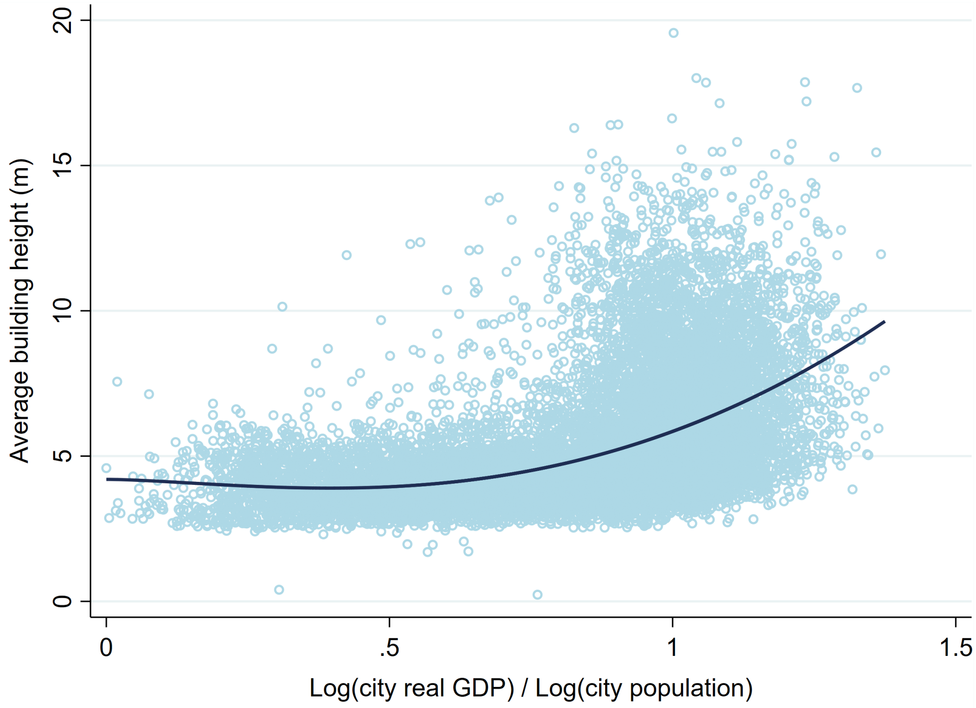


(b) Using log(city GDP) / log(city pop.) as the per capita income measure



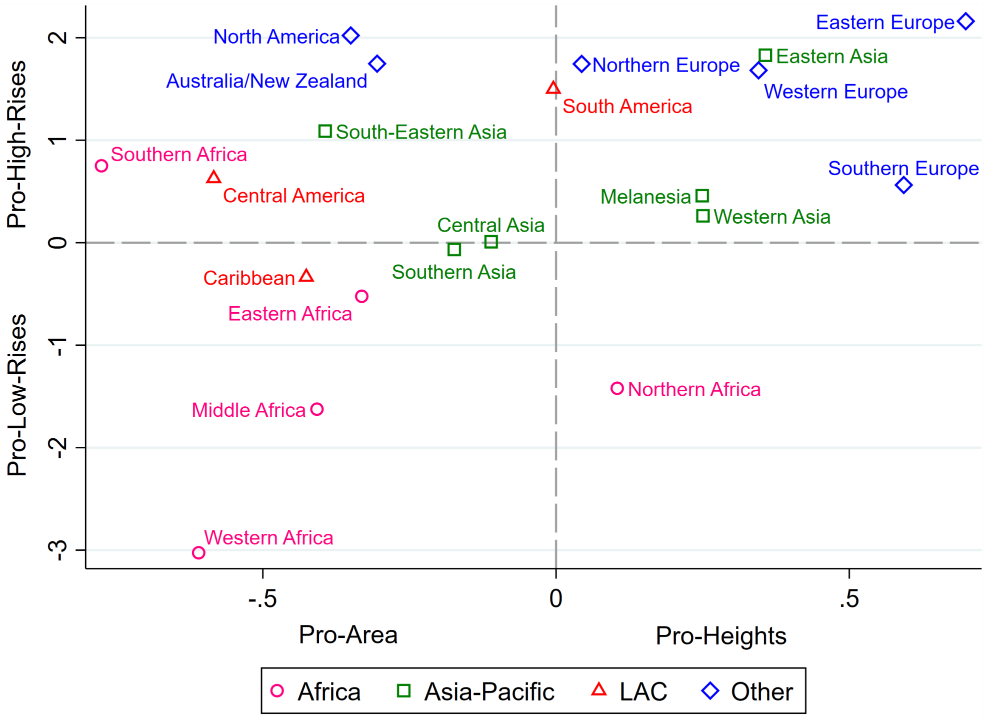
Notes: Panel A shows the relation between log(city GDP / city pop.) and log city pop. in 2015. Panel B shows the relation between log(city GDP in Bn. 2017 USD) / log (city pop.) and log city pop. in 2015. We exclude Atlantic City.

Figure C.6: City Average Building Height and City Income Per capita, 2015.



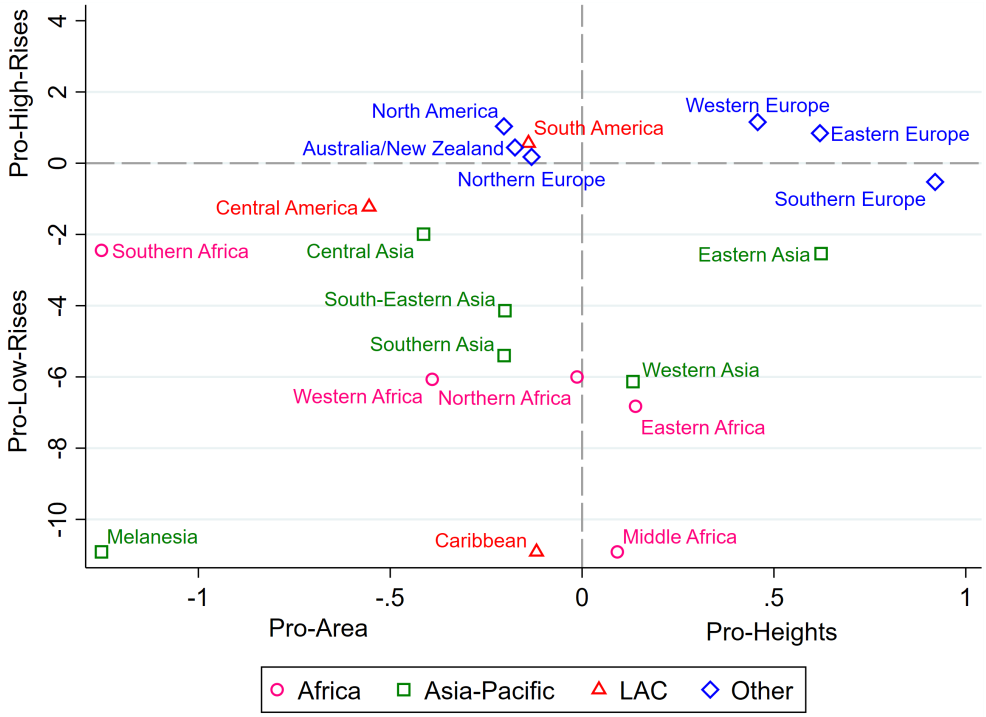
This figure shows the relation between city average height (m) in 2019 and log(city real GDP in Bn. 2017 USD) / log (city pop.) in 2015. The relation between the two is proxied by a fractional polynomial fit (using city pop. as weights).

Figure C.7: Classification of UN subregions, large cities only, 2019.



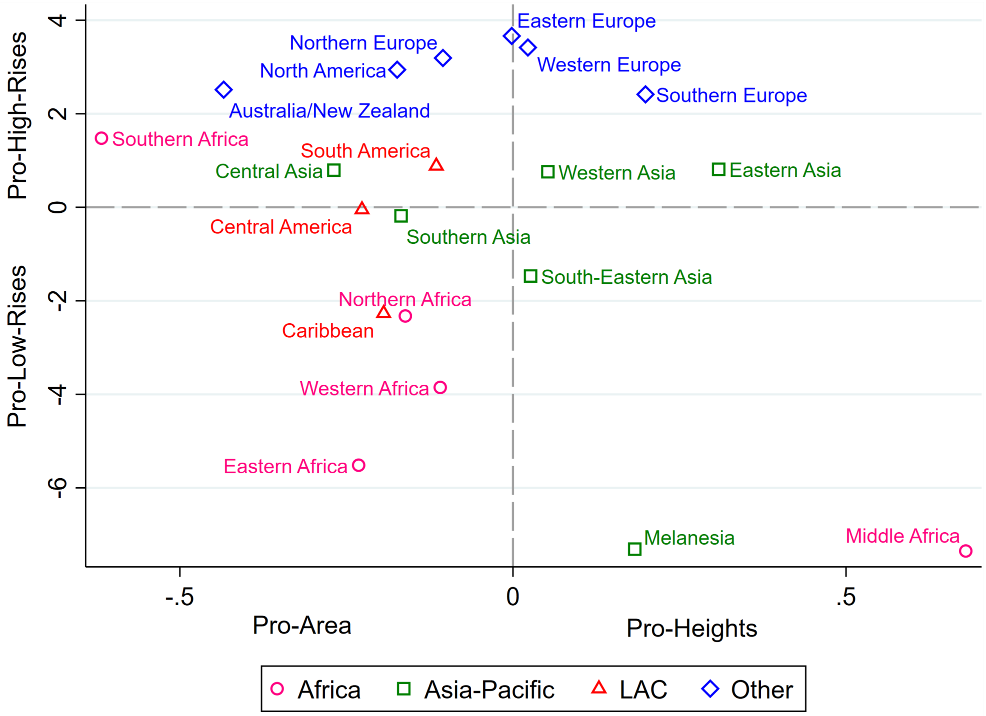
This figure shows for 20 U.N. subregions the relation between the pro-heights residuals and the pro-high-rises residuals in 2019. We report the (city) pop.-weighted avg residuals using only cities among the 15 largest cities in the country.

Figure C.8: Classification of UN subregions, small and medium-sized cities only, 2019.



This figure shows for 20 U.N. subregions the relation between the pro-heights residuals and the pro-high-rises residuals in 2019. We report the (city) pop.-weighted avg residuals using cities not among the 15 largest cities in the country.

Figure C.9: Classification of UN Subregions, Rural Areas + Small Towns Below 50K Only, 2019.



This figure shows for 20 U.N. subregions the relation between the pro-heights residuals and the pro-high-rises residuals in 2019. We report the (rural/town) pop.-weighted average residuals using localities <50,000 in 2015.